Skating propulsion: three-dimensional kinematic analysis of high caliber male and female ice hockey players

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Abstract

The aim of this Master's study was to examine the kinematics of ice-skating between high caliber male and female ice hockey players, using eighteen three-dimensional motion capture cameras. This would serve to determine if there are differences in the biomechanics of ice-skating between male and female skaters, as is seen in male and female runners. Participants performed a skating acceleration task from a static start and the first seven steps were analyzed as part of this study. Results of this study show that there are differences in the kinematics of the hip, knee and ankle during skating acceleration between male and female ice hockey players. The female skaters were more adducted at the hip through the task and more extended at the knee at ice contact compared to the male subjects. Furthermore, there are also differences in skating performance and spatiotemporal parameters analyzed, such as step width. These results have implications for skating instruction and training, injury rehabilitation and ice hockey equipment development.

Résumé

L'objectif de ce projet de recherche était de réaliser une analyse en trois-dimensions du patinage sur glace à l'accélération et de comparer les mouvements entre les joueurs et joueuses de hockey sur glace de haut calibre. Nous avons utilisé un système de capture de mouvement comprenant dix-huit caméras infrarouges sur la glace. Le but était de déterminer s'il existe une différence entre la cinématique du patinage entre les hommes et les femmes, tout comme il en existe chez les coureurs. Pour ce projet, les sept premiers coups de patins des sujets à partir d'un départ avant de hockey ont été analysés. Les résultats indiquent qu'il existe des différences de cinématique au niveau de la hanche, du genou et de la cheville entre les hommes et les femmes, pendant une accélération maximale de patinage. En tout temps, les femmes ont les hanches davantage en adduction comparé aux hommes, ainsi que les genoux plus en extension quand le patin contact sur la glace. De plus, nous avons trouvé des différences au niveau de la performance et des paramètres spatio-temporels entre les groupes par exemple la largeur du pas de patin. Ces résultats ont des implications pour les instructeurs de patinage, les entraîneurs, les professionnelles de la réhabilitation et les compagnies d'équipement de hockey.

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Contribution of Authors

Jaymee Shell, the candidate, was responsible for the research design, setup, recruitment, data collection, analysis and writing of the thesis and any other steps related to the completion of the research study and submission of this thesis as per McGill University requirements. Several other individuals provided assistance in this research.
David J. Pearsall, PhD, Associate Professor, Department of Kinesiology and Physical Education, McGill University, the candidate's supervisor, actively consulted on the research design, testing protocol and planned analysis. Julie N. Côté, PhD, Associate Professor, Department of Kinesiology and Physical Education, McGill University and Shawn Robins, PhD, Assistant Professor, School of Physical and Occupational Therapy, McGill University, were members of the candidate's supervisory committee and contributed to the design of the research protocol. Additionally, Dr. Robbins aided in developing the data processing pipelines used in this study.

Tong Ching Tom Wu, PhD, Assistant Professor, Department of Movement Arts, Health Promotion and Leisure Studies, Bridgewater State University, provided motion capture equipment. Dr. Philippe Dixon, PhD, Research Fellow, Department of Environmental Health, Harvard University, help provide MATLAB processing pipelines used for batched data analyses. Philippe Renaud, MSc, assisted with the research design, data collection and analysis of the project. Lastly, Adrien Gerbé, MEng candidate, Aleks Budarick, David Greencorn, and Daniel Boucher, MSc candidates, provided assistance during data collection and data processing.

Introduction

The game of ice hockey has substantial community, economic and physical activity promotion value within Canada, yet there is a large gap between training practice and science. For instance, the skating start is a fundamental skill; however, the optimal movement pattern(s) for forward skating propulsion have not been studied in detail over open ice surfaces. Prior exercise physiology studies have provided insight into applied coaching power training by examining predictors of skating speed in male and female athletes from off-ice tests [1-3]; however, detailed, individual, and real-time movement analysis to complement athlete training and injury rehabilitation has not been achieved. The major challenge to collecting kinematic data of skater movement is the ice arena environment's cold and humid air: problematic to the lens and electronic components of motion capture equipment. Thus, limited externally valid kinematic data of hockey players' body movement during skating exists.

Much of the prior research of ice hockey skating has predominately been focused on male athletes. However, female ice hockey participation has grown substantially since its inclusion to full medal status at the 1998 Olympic Winter Games. However, the scientific literature has not kept up with the changing demographics of ice hockey participation. To date, very limited studies [1, 4, 5], related to ice hockey skating and performance, have included female subjects, especially elite female ice hockey players. Currently, only one study has previously examined the differences between skating performance in elite male and female hockey players [6]. However, this study examined the relationship between off-ice tests to skating speed. Therefore, the purpose of this study was to perform a detailed kinematic analysis of the lower limb during skating for both male and female ice hockey players. Given that in running, female athletes have different hip biomechanics than their male counterparts, and increased injury incidences [7], we hypothesize that female ice hockey players will also display different hip kinematics in ice skating.

Literature Review

This review will begin with an overview of the biomechanics research related to speed skating, the primary focus of much earlier work. Next, previous work on ice hockey specific skating will be discussed, followed by the biomechanical measurement techniques previously used to study this skill. Finally, female-specific hockey research will be discussed. In the summary, these topics will come together to form the rational behind this study.

Biomechanics of Speed Skating

Despite ice skating's long history in Canada [8], the most detailed analysis of skating biomechanics has come from Holland, specifically with regards to the mechanics of speed skating. The speed skating stroke is similar to the ice hockey skating stride; as such much of our early understanding on ice hockey skating mechanics comes from speed skating. The main difference between speed skating and ice hockey skating is the position of the trunk. In speed skating, notably long-track skating, the trunk is positioned almost horizontal with respect to the ice, for maximum aerodynamic efficiency. However, in ice hockey, the trunk has a more vertical position, due to the position and manipulation of the hockey stick.

According to de Koning et al., there are three phases to the skating stroke (at steady-state speed): the gliding phase, the push-off phase and the repositioning phase [9]. In speed skating, unlike walking or running, the push-off force is not applied fully within the same plane as the direction of movement, rather, it is applied at an acute angle to the direction of propulsion [10]. Whereas in running gait, the movement of the feet occurs largely in the sagittal plane [11], in skating, the lower limbs extend in the frontal plane [12]. In addition, as de Koning et al. have shown, the acceleration period and steady-state skating period have different kinematic properties [10] and should be studied independently.

Regardless of the type of stride, skating is caused by extension of the lower limb, with minimal plantar flexion, in the sagittal and frontal planes [10]. A temporal phase cycle of shortening and lengthening of the hip, knee and angle flexor and extensor muscles helps achieve this type of locomotion [10]. Furthermore, in elite speed skaters, those who skated with a lower body centre of mass had a larger range of motion for both the hip and knee joints, maximizing power generation [10]. Unlike running, in skating, plantar flexion must be suppressed in order to avoid the front blade tip from catching on the ice surface, which would cause increased friction [12]. These kinematic descriptors of ice skating technique highlight the differences between running locomotion and skate locomotion and further emphasize the uniqueness of the skating locomotion [11]. Due to the differences between these types of locomotion, a more in-depth understanding of skating locomotion and movement pattern generation would be insightful for meaningful comparisons.

While skating at constant velocity has large kinematic differences compared to running [11], skating acceleration begins with push-off strides that resemble running more than steady-state skating for the first four to six steps of acceleration before transitioning into the steady-state gliding strides. de Koning and colleagues state that skating movement has two key movement performance properties: the extension velocity of leg and the rotation velocity of the leg within the sagittal plane, relative to the centre of the body. In the running-like acceleration strides, the rotational velocity contributes more than the extension velocity to the overall velocity of the skater, however, in the gliding steady-state strides, the extension velocity contributes more to the overall velocity [10].

One of the main differences between skating and running locomotion is the relative position of the foot to the body at the moment of push-off. According to Denny [12], the most efficient push-off angle for skating is at 35° from the direction of propulsion. Theoretically, at this angle, the power propelling the skater is optimized (i.e. minimized backward drag and friction forces with respect to forward push-off force). However, this does not take into account the efficiency of the muscles, the length of the moment arm, nor any other physiological factors [12]. Furthermore, steady-state speed is dependent on multiple factors, such as endurance, strength, technique, and friction [12]. This push-off angle is in contrast to the position of the foot during running, at toe-off, where the foot is pointing forward in the direction of movement, not at an angle, like the skate boot.

While the angle of push-off affects the propulsion of the skater, the duration of the push-off stride also impacts the mechanical power, power distribution and energy expenditure of the athlete. For example, as part of his thesis, Zuiker had ten elite speed skaters skate using three different push-off techniques at steady-state skating: small strides, self-selected strides width and wide strides [13]. Power, in the forward, sideways and upward directions, was calculated relative to body weight, as well as mechanical power (using a 3D power balance model) and energy efficiency (based on steady-state heart rate). The amount of forward power and sideway power was significantly different for all three techniques examined. As the push-off strides increased in length, there was a corresponding increase in sideways power generated by the skater. Therefore, the wide-off technique generated the most power of all the strides, but 72% of this power was in the sideways direction [13]. The small push-off technique had the lower total mechanical power and the highest forward power component, however it also had the highest energy expenditure/stroke, so it is not the most efficient technique [13].

Original work on speed skating mechanics has focused on a variety of factors, such as speed, force, power, muscular coordination and friction. With respect to speed, van Ingen Schenau et al. [14] examined how female speed skaters the control their skating velocity. By examining the same group of ten skaters, each skating in four different distance events (500m, 1500m, 3000m and 5000m), they could examine which parameters determine the difference in speed between subjects of the same caliber when racing the same distance and how speed is regulated by the same skater when their race distance changes. Skaters control their speed by changing their stroke frequency, not the amount of work generated per stroke. However, inter-individual differences between athletes of the same caliber are due to differences in push-off mechanics [14], again highlighting the importance of studying the biomechanics of the skating stride. As both van Ingen Scheneau [14] and Denny [12] alluded to technique does play a role in determining steady-state skating mechanics and speed. A more in-depth understanding of the skating stride, during acceleration and steady state, will help elucidate the contributions of the hip, knee and ankle to skating performance, which could impact training and coaching.

Subsequent studies of the biomechanics of speed skating focused on limb-segment coordination and muscle force during speed skating. In a study by de Boer and colleagues of muscle coordination during skating [15], it was found that the skate push-off was constrained due to the absence of plantar flexion in this movement, and maximal knee extension actually occurred only after the skate blade has been lifted off the ice [15]. This limited plantar flexion is one of the parameters that makes skating unique compared to running locomotion [11]. Using strain gauges on the front and back of the skate and a link-segment model, the torque were calculated for the hip, knee and ankle joints during push-off. During push-off, there was a temporal order of power generation at the joints of the lower limb. Hip power was delivered over a large portion of the stroke, while knee power occurred over the last 250ms and with ankle power contribution only during the last 150ms of the stroke [15]. This temporal pattern of limb movement has also been shown in muscle activation during skating, in both novice and elite speed skaters [9]. The electromyographical data revealed a proximal to distal temporal order of activation, similar to that seen in a vertical jump. The temporal order was not affected by the skill difference of the skater, however the elite skaters were able to generate more force during their stroke [9].

Ice Hockey Skating

Skating is one of ice hockey's most fundamental skills [8]. Therefore, an in-depth biomechanical understanding of skating is important for exercise scientists, coaches, trainers and athletes. Skating at steady-state speed is a biphasic movement; it has a support phase, either single or double support, and a swing phase [8]. Skating is a novel type of locomotion because the each foot's push-off orientation is not primarily in the direction of movement, as in walking and running. Skaters propel themselves by generating a ground reaction force component that is perpendicular to the long axis of the skate blade. This is achieved by externally rotating the hip to enable digging in the medial blade edge and pronating the foot during leg extension [8].

Skates are tools that allow the skater to take advantage of the different frictional properties of the ice surface [8]. When the skate blade's long axis is parallel to the direction of motion, the coefficient of friction is very low and the skater can glide, whereas when the blade is oriented obliquely to the direction of motion, a sufficient ground reaction force can be generated for propulsion [11]. It is crucial for hockey players to become proficient at forward skating because this skill forms the basis of executing other skills, such as puck handling, passing, shooting, stopping, turning and pivoting [11]. While the kinematic patterns for optimal skating performance have yet to be established, an indirect description of the gait pattern of skating has come from the design of a humanoid skating robot. Similar to walking gait, skating is characterized by alternating periods of single support and double support. The single support phase is much more unstable than the double support phase. Unlike walking, the skate blades use a large lateral force to propel the skater forward and then help reduce friction so they can glide. The ground reaction forward applied to create locomotion is not in the direction of movement [16]. Based on research into the cyclic pattern of skating biomechanics, there are five important parameters to consider when evaluating skating gait: period, hip height, glide length, glide angle and push-off angle. The hip height is important to study, because a low hip height means that higher torques can be generated at the hip and knee joints, by the quadriceps and gluteus maximus muscles [16]. Kinematic research of male and female skating should include these variables, in order to help understand the optimal skating biomechanics.

While much of the understanding of skating biomechanics has been extrapolated from speed skating to ice hockey, the hockey skate is different from a speed skating boot and blade properties. The high cut design of the ice hockey skating boot, compared to the speed skating boot, provides greater medial and lateral support for the ankles as well as more protection from being cut, but limits plantar and dorsiflexion during push-off [8]. In comparison to the long, flat speed skate blade, the hockey skate blade is shorter and has a convex curvature (i.e. rocker) that it is visibly curved upward at both ends. The hockey blade's bottom surface is double edged, separated by a shallow hollow groove: this permits sufficient blade-to-ice grip for the skater to turn and pivot without slipping. The hockey blade's rocker radius and radius of hollow can be customized to the player's need, style of play and the ice conditions where they skate. When gliding, one of both of the edges of the blade may be in contact with the ice [8]. The hockey skate blade design makes this type of skate less stable than a speed skate, but allows for increased maneuverability and increased turning capability [12].

The hip abductors and extensors are the prime movers for skating, along with stabilization from the hip flexors and adductors, which help decelerate the leg. Adductor strains may be caused by the large eccentric contractions during the deceleration of the leg [17]. This view is supported by Sim et al. [18] who said that ice hockey players are prone for noncontact musculoskeletal injuries due to the large acceleration and deceleration forces that occur during skating. Wilcox et al. [19] compared the strength and range of motion of NCAA D3 male hockey and soccer players. Soccer players were chosen as a comparison group due to the similar intermittent nature of a soccer game and the similarity in length to a hockey game [19]. Regardless of sport, all athletes' dominant leg had a more equal adducton:abduction strength ratio than their non-dominant leg, which was previously identified as a risk factor for hip adductor injuries in male hockey players [17]. Overall, hockey players had less strength in hip adduction, sitting hip flexion and lying hip flexion than soccer players. Hockey players had greater hip adduction range of motion than soccer players but less range of motion in external rotation than soccer players. Based on their hip strength and range of motion, hockey players have a more at-risk profile for non-contact hip injuries than soccer players [19]. Furthermore, the decrease in external rotation range of motion for hockey players may be a risk factor for femoroacetabular impingement (FAI) [19].

It has previously been hypothesized that repeated eccentric contractions of the leg muscles during skating may cause hip adductor muscle injuries in ice hockey players

[20]. The purpose of Chang et al. [20] was to examine the relationship between skating speed, muscle activity and lower limb kinematics of the hip adductor muscles in ice hockey players. Furthermore, it was hypothesized that hip joint kinematics may help provide an explanation as to why hockey players are predisposed to groin muscle injuries [20]. Because hockey skate blades offer a small base of support that is unstable in the medial-lateral direction, the medio-lateral muscles of the hip, knee and ankle must be active in maintaining balance [20]. On a skating treadmill, seven collegiate ice hockey players skated at three speeds, considered slow (3.33 m/s), medium (5.00 m/s) and fast (6.66 m/s), while EMG and kinematic data was collected. An increase in skating speed corresponded to an increased in muscle activity for all muscles studied, however the adductor magnus muscle had a disproportionately larger increase in peak muscle activation and had prolonged muscle activity [20]. Furthermore, with increased skating speed, there was a significant increase in the stride rate and length, which was achieved without an increase in hip, knee or angle range of motion. Overall, increased skating speeds resulted in increased muscle response, total strain and eccentric load on the adductor muscles, which could be related to groin injuries in ice hockey players [20].

However, this study was performed on a skating treadmill, which has previously been shown to differ slightly from on-ice skating [21], so it is unknown if we can generalize these results to ice hockey players. With technological advances that have occurred since this study was published, researchers are now better equipped to study the kinematics and muscle activity of ice hockey skating in the natural environment. Equipment that has been previously constrained to the laboratory need not be anymore, as they have the capacity and resolution to function in an environment where they were previously restricted. However, few studies have undertaken the endeavor of setting up motion capture cameras in the arena, despite the insightful information already derived from kinematic research. Further research into kinematics could elucidate the optimal movement patterns for skating and have strong value for coaches, trainers and rehabilitation professionals.

Femoroacetabular impingement (FAI) is a condition that occurs when the femoral head repeatedly comes into contact with the acetabulum during hip internal rotation [22]. This results in hip pain in the affected individual. It has been hypothesized that athletes in high-impact sports are prone to developing FAI [22], with ice hockey players being a high-risk group, due to the biomechanics of skating. The at-risk position for developing FAI includes: (1) abduction and external rotation of the hip and (2) flexion and internal rotation of the hip [23]. Hockey players are at an increased risk for developing FAI, because hip abduction and external rotation occurs during skating push-off and hip flexion and internal rotation occurs during the recovery phase when gliding [23]. While the goal of this study is not to predict FAI or to study athletes who currently have this condition, the quantitative measures of hip kinematics established in this study can be used in future studies related to this injury. Before the biomechanics of FAI can be studied and understood, the biomechanics of skating in a healthy population must be addressed.

According to Ayeni et al. [22], the odds of developing FAI in competitive ice hockey players is 2.5 times greater than in sedentary controls. Similarly, Stull et al. [23] noted that the increased risk of FAI in ice hockey players might be related to the biomechanics of skating and the repetitive nature of the motion. Youth male hockey players also display the at-risk position of the hip during a skating start, as measured by kinematic analysis via infrared cameras and reflective markers on a synthetic ice surface [23]. As the players accelerated from a standing position, their vulnerability to injury increased due to an increased range of motion of the hip for flexion/extension and internal/external rotation and an increase in the speed of these movements [23]. The higher incidence rate of FAI in ice hockey players further emphasizes the need for biomechanical studies of ice hockey skating, in both healthy and affected populations. While we know that the biomechanics of skating is a risk factor for developing chronic overuse injuries, there is a lack of detailed kinematic analyses of ice-skating in the literature. By addressing this issue, researchers can not only have a better understanding of skating performance and movement, but also why ice hockey players may be at an increased risk for developing these debilitating injuries.

Ice Hockey Skating Biomechanical Measurement Techniques

One of the earliest studies on hockey biomechanics, by Marino [24], investigated predictors of successfully completing a standard start using a 2D film analysis. He found that a high stride rate, significant forward lean and placement of the recovery foot under the body at the end of the single support phase predicted better starts in ice hockey players [24]. While the research technique is much more primitive than the motion capture technology used today, this study represents the first analysis of skating biomechanics and kinematics. With respect to skating speed, previous literature has identified significant predictors of skating speed from a standard start [25]. Hip flexion strength, ankle dorsiflexion, hip adduction and abduction flexibility, knee flexion and extension flexibility were significant predictors of skating speed over 25m [25]. Furthermore, there were significant differences in the skating biomechanics when participants skated with and without a hockey stick [25]. Therefore, future research protocols should include a hockey stick for participants, to mimic in-game skating, as closely as possible and to ensure the data is as externally valid as possible.

While limited, there have been some previous investigations into ice hockey kinematics biomechanics [20, 26-28]. Upjohn et al. [26] sought to compare the lower limb kinematics of high and low caliber male hockey players. According to Upjohn et al. [26], the kinematics of skating refers to the linear and angular motions of the body during each skating stride. They skated at self-selected speed on a treadmill adapted for ice hockey skates [26]. Using Direct Linear Transformations from multiple video camera views of the skater to obtain 3D kinematics, it was noted that the high caliber skaters had significantly higher skating velocities than the low caliber skaters, despite a similar stride rate. However, the stride length and width for the high caliber skaters was significantly higher and wider, respectively, than the lower caliber skaters. Furthermore, the high caliber skaters had greater hip flexion at weight acceptance, greater knee extension and plantar flexion at propulsion and a greater range of motion for the knee and ankle.

Overall, there were significant kinematic differences between the high and low caliber skaters. It was recommended that low caliber skaters could improve their skating skills if they trained to lengthen their stride and try and increase their overall joint range of motion through the stride [26].

However, the extent to which skating ergometer measures can be extrapolated to on ice performance has been raised [21]. Therefore, more recent data has been collected in the natural setting for ice hockey players, the arena. One of the first studies to collect data using a portable system to study skating biomechanics examined the kinematics of the ankle during skating acceleration [29]. By placing electrogoniometers in the sagittal and frontal planes of the ankle, a movement profile of elite ice hockey players could be established. The skaters performed an acceleration task, starting from a static position and accelerating maximally in the forward direction. While not significant, the kinematic profile of the ankle changed as the skater accelerated from a static position [29]. A further understanding of the kinematics of the ankle during skating is important to establish for equipment manufacturers and rehabilitation professionals alike.

Stidwill et al. [28] developed a portable system to estimate ground reaction forces during ice hockey skating that would function in the cold arena environment. Using multiple strain gauges adhered to the skate blade holder and a portable data acquisition system in a backpack, the vertical and medial-lateral forces on the blade holder were determined. These results were compared to those from a force platform and it was established that this system could accurately estimate the ground reaction forces when skating [28]. This study was able to bring technology previously constrained to the laboratory and modified it in order to collect data in the cold and humid arena environment.

Similarly, Robert-Lachaine et al. [30] used a portable data logger to collect force and ankle kinematic information from ice hockey players skating in an arena. By modifying the skate design to allow for increased plantar and dorsiflexion, measurement of dynamic forces using strain gauges and ankle kinematic using electrogoniometers, performance and biomechanical changes and biomechanical were be evaluated [30]. Skating performance is crucial in elite ice hockey players and is likely related to both the skill and conditioning of the athlete, as well as the equipment they are wearing [30], so evaluating performance differences using modified equipment is insightful for equipment manufacturers. In this study, the maximal plantar flexion, plantar dorsiflexion range of motion and plantar flexion angle at peak force production all differed significantly between the two skate models. Most importantly, there was an increase in dorsiflexion during the weight acceptance phase of the stride and an increase in plantar flexion during push-off [30]. However, these kinematic changes, coupled with changes in force production with the modified skate, did not translate into improved times for the skating task performed. While understanding the kinematics of the ankle and other lower body joints is important to understand the optimal biomechanics of ice skating, it is also important to identify variables that significantly affect performance, such as skating speed, as this information is important to trainers and coaches, who can use it to help develop young athletes.

Subsequently, in a second study, Stidwill et al. [27] compared skating kinetics and kinematics on an actual ice surface to a synthetic ice surface in a laboratory, which can be installed in a controlled laboratory setting for biomechanical research [27]. While Stidwill et al. found comparable kinetic and kinematic skating variables between the synthetic and actual ice surfaces, only short-distance skills could be executed on the synthetic ice, due to limited space [27]. It was noted that artificial ice installed in a lab could overcome some of the many challenges to efficiently study skating biomechanics on ice, such as: cost of ice rental, transport of equipment, equipment set-up, cold damage to equipment and difficulties calibrating a larger capture area and controlling ambient lighting [27]. However, the movements that can be studied indoors are largely limited by the space. Furthermore, Renaud et al. [31] was successfully able to bring, calibrate and collect kinematic data from ten Vicon® infrared cameras. None of the factors mentioned by Stidwill et al. [27] as detractors to studying skating biomechanics in the arena were mentioned by Renaud et al. [31] as limitation in that study. It represents the first collection of skating biomechanics data using passive reflective motion capture technologies.

While the studies aforementioned show the progression of the scientific literature in the field of skating biomechanics, coupled with increases in technology and measurement techniques, none of these studies have included female participants in their cohorts. Future research needs to include players of both sexes in order to fully understand the biomechanics of the lower limb during skating and any differences that may be related to sex.

Recently, the feasibility of using infrared motion tracking cameras in outdoor winter snow environment for ski cross starts [32], and within ice arenas for skating starts [31] and shooting tasks [33] have been demonstrated. Renaud et al. [31] collected kinematic data of the lower body for the first two strides of skating starts over 5 m, however, the cohort did not include any female subjects. Nonetheless, this study [31] is crucial because it represents the first collection of skating data using a passive marker motion capture system on an actual ice surface. While the equipment setup was challenging for these researchers, and the environmental conditions of the arena were not ideal for motion capture, the study compared the lower limb kinematics of elite and recreational male ice hockey players. Unsurprisingly, the high caliber skaters performed the task faster and with a higher velocity than the low caliber skaters. The kinematic patterns of the lower limb joints were similar between the groups, but the rate of movement was higher in the elite players [31]. However, in this study, only the first four steps were captured due to the number of cameras. Furthermore, because the upper body was not studied, the center of gravity was not calculated and was approximately used the sacral markers. This study will have increased cameras to capture the entire acceleration phase of skating, as well as a more detailed marker set-up. Also, by having female and male participants in our cohort, we will be able to get a detailed analysis of the kinematics of the lower limb during skating acceleration, and also identify differences between the two sexes.

To date, there has only been one other reported study that using a 3D motion capture system on the ice [33]. Swarén et al. collected full body kinematic data from two professional male ice hockey players and analyzed their shooting technique. These researchers reported that their on-ice setup worked well in the harsh arena environments, but it took approximately fifteen hours to setup the system [33]. This is in contrast to Renaud et al. (2015), who had a mobile setup unit that took approximately one hour to setup and the cameras we setup for each data collection period.

While they did not collect motion capture data, Buckeridge et al. [34] measured muscle activity, plantar pressure, and angular displacements on the ice using a mobile unit that participants could wear on their back. This study highlights a literature gap with respect to skating biomechanics, due to the dynamic nature of the sport and the unique environment, because it is lacking motion capture data to provide insightful information on skating performance and the variables that contribute to skating performance. This study took multiple technologies previously constrained to the laboratory and brought them all onto the ice, using a mobile data acquisition unit worn in a backpack that could synchronize all the data. This unit did not constrain their skating style, so the study achieved a realistic and externally valid on-ice data collection [34]. The participants in this study were high level and recreational male hockey players and any significant differences between the groups were interpreted as a variable that differentiates elite skating performance from recreational performance. Notably, the high caliber group had greater hip abduction velocity during propulsion, greater hip extension at toe-off and greater knee extension velocity during acceleration [34]. Similarly to other studies on ice hockey skating and biomechanics, there were no female participants in the cohort.

While these studies [31, 33] refute the claim Upjohn et al. [26] made regarding the limited application of three-dimensional motion capture on the ice, none of these studies have included female subjects, nor have they used a full-body marker to analyze skating technique. As previously mentioned, understanding the biomechanics of skating in male and female ice hockey players is important for the athletes, coaches, trainers, rehabilitation professionals and for filling in a gap in the scientific literature. A detailed kinematic analysis of ice hockey skating could help develop the performance of high-level athletes, optimize the skating instruction of young hockey players and help understand why hockey players are prone to developing chronic overuse injuries. However, detailed research that could bridge the gap between the current literature and these issues has yet to be performed.

Women's Ice Hockey

According to Hockey Canada's History of Women's Ice Hockey, the first documented women's hockey game occurred in 1892 in Barrie, Ontario, Canada. The first International Ice Hockey Federation (IIHF) World Women's Championship took place in 1990, and women's ice hockey popularity surged after the announcement by the International Olympic Committee and named women's ice hockey a full medal sport, beginning at the 1988 Olympic Winter Games in Nagano [35]. Despite women's ice hockey's recent surge in population, there have been few studies on hockey performance and skating biomechanics that have included female participants and many of the studies performed have investigated predictors of skating performance in female ice hockey players, using regression equations [1, 4, 5]. There has yet to be an analysis of the biomechanics and kinematics of ice-skating in female hockey players. As skating is one of the most fundamental hockey skills, regardless of sex, studies that include female subjects are essential to understanding skating biomechanics and using that information for developing coach tools and techniques [8].

The pioneering study in this field, by Bracko [4], compared skating in elite female hockey players to non-elite female hockey players. Elite players were found to be older, more experienced hockey players, faster skaters, more agile skaters and had a higher anaerobic capacity, as measured using the Watson and Sargeant formulas [4]. However, when the two samples were age-matched, the only significant difference between the two groups was the relative anaerobic capacity. Because of the small sample size in this study, the author suggests that future research should collect data on a larger population of female hockey players. By identifying the off-ice fitness variables that predict skating performance, trainers and coaches can adapt physical and on-ice training programs to ultimately improve skating performance in female hockey players.

A subsequent study attempted to identify off-ice variables that could predict acceleration, speed, agility and on-ice aerobic capacity in sixty-one competitive female ice hockey players [1]. The 40-yard dash was a significant predictor of skating speed and negatively related to on-ice aerobic capacity and the vertical jump test was positively related to on-ice aerobic capacity [1]. The authors concluded that off-ice sprinting speed was the strongest predictor of skating speed in female youth hockey players.

Follow-up research performed by Geithner [5] over seven years aimed to determine if anthropometric and off-fitness tests predict on-ice skating performance in 192 elite collegiate female hockey players. Acceleration was significantly predicted by 40-yard dash time, BMI and the relative muscularity of the build, while speed was significantly predicted by 40-yard dash time, biacromical breadth and the sit-up fitness test. According to this study, in general, better on-ice skating performance was associated with faster off-ice running speed, relative muscularity of build (mesomorphy), biacromial breadth, abdominal muscular endurance and lower BMI [5]. However, the significant predictors only accounted for 22.3-34.2% of variance in on-ice skating performance, so anthropometric and fitness are not enough to account for skating skill and speed.

While it is important to understand the predictors of skating speed and performance, in order to develop effective training techniques, this is not sufficient to understanding the biomechanics of skating and its unique form of locomotion. Studying the kinematics of lower limb segments and comparing them across different age, sex, and skill level groups can only achieve this. To collect externally valid data on skating biomechanics, a three-dimensional infrared motion capture system must be set-up in the arena with a capture volume sufficient to capture the first eight steps from a static start.

To date, only one study has compared predictors of skating performance in both male and female hockey players [6]. While men had significantly higher absolute physiological values, such as peak muscle torque, aerobic and anaerobic fitness tests, when these values were reported as a percentage of lean body mass (%LBM), the physiological differences between the sexes disappeared [6]. This study found that the off-ice fitness tests were able to predict skating performance in females but not males. The LBM of the two cohorts, regardless of sex, had a similar capacity to produce strength and aerobic power on the tests performed. While the on-ice performance was significantly different between the two sexes, the physiological values measured could not account for these differences [6]. When comparing males and females, one has to consider the differences in body size, body composition and player experience, in order to make the groups comparable. It is interesting to note that there were significant differences in performance between the male and female groups; however, these differences could not be explained by the physiological measures taken, as the differences disappeared with normalization [6].

In the limited studies published [1, 4, 5], off-ice and anthropometric measures predicted a small proportion of variance in skating performance among female hockey players and physiological values could not account for the differences in performance between male and female ice hockey players. Anatomically, it is known that the male and female pelvis has evolved for different roles and this difference has been postulated as a cause of differences in running mechanics and injury patterns in male and female runners [36]. However, this phenomenon has yet to be examined in ice hockey skating. Since the anthropometric, fitness and physiological variables have yet to explain the performance differences in ice-skating a kinematic analysis of the lower limb in ice-skating is warranted.

Given the increase in popularity in ice hockey, especially among youth, as well as a heightened awareness about the potential dangers of concussions in the mainstream media, injury profiles in hockey players are worth studying. In a review on injuries in female hockey players, attention is brought to the previous work that has shown male and female hockey players to unexpectedly have a similar injury profile, despite there being no body checking in women’s hockey [37]. The most common injuries in female collegiate ice hockey players are hip and groin strains [37].

According to Abbott [37], adductor strains are the second most common game injury, after concussions, and most common practice injury in female hockey players. This injury occurs at a similar rate in both female and male hockey players, except in one study found that female hockey players had a higher absolute rate of adductor strains [38]. Compared to the hip abductors and external rotators, hip adductor muscles achieve the highest relative amplitude and muscle activation during skating [20], therefore it is not surprising that this muscle is often injured in ice hockey players [37]. However, studies on risk factors for adductor injuries have not included female hockey players, so it is not known why these occur more frequently in this population [37].

While Abbott [37] claims that forward skating biomechanics are the same for both male and female hockey players, this has yet to be proven in the literature because there are very few studies that have used three-dimensional motion capture on the ice surface and none of them have included female subjects. Based on the differences in running mechanics and injuries between male and female runners, due to the anatomy of the pelvis, Abbott's claim about skating biomechanics is unsubstantiated. Due to the unexpected similarities in injuries between male and female hockey players [37], as is seen in running [36], a comparison between the biomechanics of male and female skating is warranted. This study should include high caliber male and female hockey players and the data should be collected in an arena, not on a skating treadmill or an artificial ice surface using three-dimensional motion capture. Furthermore, in a study on the epidemiology of male and female youth hockey injuries, the authors called for future research to investigate equipment modifications for female-specific equipment [39], further emphasizing the need to study the female hockey player population and to compare them to their male counterparts.

Summary

Much of the early understanding of ice skating biomechanics has come from the research on speed skating. It is now understood that skating locomotion is different than running at steady state speed, however, it may be similar during the acceleration phase of skating. Due to the fundamental differences between skating acceleration and constant velocity skating, it is crucial to study them independently, as they have different kinematic properties. Forward ice hockey skating is the most basic and fundamental skill for an athlete to learn, as it forms the basis for almost all the other dynamic movements performed during a game. The shape of the skate boot constrains the movement of the ankle and differentiates this locomotion from running. While the optimal kinematic patterns for skating have yet to be established from externally valid data, collected in an arena, the muscle recruitment patterns of hockey players have shown that the hip abductors and extensors are highly taxed during skating. It is possible that the repeated eccentric strain placed on the muscles of the lower limbs is contributing to an increased risk for ice hockey players to develop chronic overuse injuries, especially at the hip joint. However, there is a current lack of solid biomechanical data on the movement of the hip during skating. Furthermore, while there are limited studies that have tried to study the hip movement during skating, none of them having included female participants, despite the increasing popularity of the sport among female athletes worldwide.

With technological advances, measurement tools previously constrained to the laboratory have gradually been brought into the arena to collect externally valid data on skating biomechanics. However, these studies are lacking in their research design, as they have yet to include female participants in their cohort. While performing data collection in the arena is a large milestone for this area of research, the inclusion of female and male players is essential to understanding the kinematics of the lower limb during skating and how this relates to skating performance.

While limited, studies have begun including female hockey participants in their cohorts, as female hockey is growing in popularity worldwide. However, in the studies published to date, anthropometric, fitness and physiological variables have yet to explain the performance differences between female hockey players of varying calibers and between male and female hockey players of a similar caliber. In running literature, it is known that the anatomical differences between males and females affects running mechanics and injury profiles. The biomechanics of running locomotion have been studied more extensively than ice hockey skating locomotion, due to the constraints of collecting kinematic data in the arena environment. However, with recent technological upgrades to motion capture cameras, it is now possible to use these cameras for data collection in an arena. Therefore, an in-depth analysis of skating biomechanics, with a focus on hip kinematics, is warranted in both male and female ice hockey players performing a forward skating task.

Research Article

Skating propulsion: Three-dimensional kinematic analysis of high caliber male and female ice hockey players

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Abstract

Forward skating is a fundamental skill for all ice hockey players, yet the biomechanics of this skill have yet to be studied in female ice hockey players. Furthermore, the optimal movement patterns for this skill are not yet understood. Hence, the purpose of this study was to evaluate the kinematics of ice hockey skating in relation to the sex of the skater. Male (N=9) and female (N=10) high caliber ice hockey players performed five maximal skating acceleration starts. An eighteen-camera motion capture system placed on the arena ice surface captured kinematic data from a full-body marker set during the first seven steps. This detailed analysis of hip, knee, and ankle kinematics, revealed differences between the cohorts of subjects. While all skaters had their hip in an abducted position through the trial, the females had significantly less hip abduction throughout the trial, and had significantly more knee extension at ice contact. This is related to a significantly shorter step width for the female skaters, despite normalizing the distance to body height. This study is the first detailed kinematic analysis of ice-skating in male and female ice hockey players. The kinematic movement patterns observed, regardless of sex, further emphasize the uniqueness of skating as a type of locomotion.

Introduction

Despite ice skating's long history in Canada [8], the majority of skating biomechanical analyses has come from research groups in the Netherlands, specifically with regards to the mechanics of speed skating. Much can be gleaned from these studies to aid skate training in ice hockey; however, context differences between these skating sport cousins indicate that fundamental skating technique differences exist; for example, in ice hockey, the trunk is in a more vertical position while skating so as to manipulate the hockey stick. Hence, detailed ice hockey specific skating mechanic studies are justified. Further review of past ice hockey research clearly shows a bias towards male only test subjects and a limited number of published studies on ice hockey performance in women [1, 4, 5]. With the surge in participation in women's ice hockey, studies should include both male and female athletes to better understand skating biomechanics in general, as well as potential skating technique sex differences that can guide specific training techniques to enhance performance and reduce injury risks players [6, 8, 37, 39].

Characteristic movement phases or cycles define locomotion skills. With respect to ice skating, there are three phases to the skating stroke (at steady-state speed): the gliding phase, the push-off and the repositioning phases [9]. In skating, unlike walking or running, the foot's push-off force cannot be applied coincident to the forward direction of movement; rather, it is applied at an acute angle [10, 12] due to the properties of the ice surface. Theoretically, when the skate push-off is at 35° to the forward direction of movement, the power propelling the skater is optimized mechanically. However, this does not take into account physiological factors such as the efficiency of the muscles [12]. In running gait, the movement of the feet occurs largely in the sagittal plane [11], whereas in skating, the lower limbs extend in the frontal plane [12]. In addition, as de Koning et al. have shown, the acceleration period and steady-state skating period have different kinematic properties [10] and should be studied independently. As well, in skating, unlike running, plantar flexion push-off must be suppressed in order to avoid the blade dragging on the ice surface [12]. These kinematic descriptors of ice skating technique emphasize the uniqueness of skating locomotion [11].

It is crucial for hockey players to become proficient at forward skating because this skill forms the basis of executing other multi-task skills, such as puck handling, passing, shooting, stopping, turning and pivoting [11]. This is not a trivial task, as most novice skaters will attest. The locomotor challenge of skating is substantial; for example, though much progress has been made in autonomous robotic locomotion over ground, limited success has been in development of “skating” robots [16]. In humans, the hip extensors and abductors muscles are the prime movers for skating, along with the hip flexors and adductors muscles for stabilization.

Skating’s exaggerated side-to-side gait is implicated in distinctive overuse injury risks. For example, adductor muscle strains may be caused by the large eccentric contractions during the deceleration of the leg [17, 18, 20]. As well, ice hockey players have a greater at-risk profile for non-contact hip injuries than other game sports such as soccer players [19]. Furthermore, the decrease in external rotation range of motion for hockey players may put them at greater risk for femoroacetabular impingement (FAI) [19], a condition that occurs when the femoral head repeatedly comes into contact with the acetabulum during hip internal rotation [22]. Hockey players may be prone to developing FAI because of the repetitive concurrent hip abduction and external rotation positions during skating push-off, as well as concurrent hip flexion and internal rotations during the recovery phase when gliding [23].

Comprehensive kinematic movement analyses of skating have proven valuable in identifying key movement parameters related to performance [20, 26-28]. For example, Upjohn et al. [26] compared the lower limb kinematics of high and low caliber male hockey players skating on a treadmill adapted for ice hockey skates. Greater skating velocities were achieved not through higher stride rates, but rather due to greater hip flexion at weight acceptance, greater knee extension and plantar flexion at propulsion and a greater range of motion for the knee and ankle. However, the extent to which skating ergometer measures can be extrapolated to on ice performance has been questioned [21]. An alternative approach is use portable measurement systems to estimate body movement. For example, Buckeridge et al. [34] measured muscle activity, plantar pressure, and angular displacements on the ice using a mobile unit that participants could wear on their back. Of the male athletes tested, notably the high caliber group had greater hip abduction velocity during propulsion, greater hip extension at toe-off and greater knee extension velocity during acceleration [34].

Recently, the feasibility of using infrared motion tracking cameras in outdoor winter snow environments have been demonstrated for ski cross starts [32], and within ice arenas for skating starts [31] and shooting tasks [33]. From male ice hockey players, Renaud et al. [31] collected kinematic data of the lower body for the first two strides of skating starts over 5 m. This study [31] is notably the first to collect ice hockey skating data using a passive marker motion capture system on an actual ice surface for research purposes. While the equipment setup was challenging for these researchers, it succeeded on obtaining detailed lower limb joint and segment kinematics of elite and recreational male ice hockey players for the first four skating acceleration steps. Building on the work of Renaud et al. [31], the purpose of this study was to compare lower limb kinematics in female and male hockey players, by conducting 3D motion capture on the ice surface, using a full-body marker set.

Methods

Participants

Skate acceleration data for ten (10) elite female and nine (9) elite male ice hockey players were collected during on ice testing (Table 1). These high caliber hockey players were university varsity athletes (Canadian Interuniversity Sport league). Participants who had any major lower limb injuries were excluded from participating in the study. Prior to testing, an ethics certificate was obtained from McGill University and participants were required to read and sign a consent form in accordance with the Tri-Council Policy Statement on Ethical Conduct for Research Involving Humans.

Table 1. Participants' Demographic Information

Parameter	Female (Mean ± SD)	Male (Mean ± SD)	hyP value
Age	21 ± 1	22 ± 1	p = .452
Years of Hockey Experience	14 ± 1	16 ± 2	p = .016 *
Height (m)	1.72 ± 0.07	1.81 ± 0.08	p = .011 *
Lower Limb Length (m)	0.93 ± 0.05	0.97 ± 0.05	p = .148
Weight (kg)	71.2 ± 10.4	81.5 ± 8.4	p = .031 *

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

Instrumentation

An eighteen camera Vicon Motion Capture System (Vicon ©, Oxford, UK) was set up on the arena ice surface for data collection. This included 2 T40S cameras, eight T20 cameras and eight T10 cameras. The cameras captured data from 14mm passive reflective markers at 240Hz. The system was calibrated prior to each of the testing sessions. The calibrated capture volume was approximately 3m wide by 15m long and 2m high to track the first seven skating steps from a static standing position. Two digital cameras (Go Pro

Hero3+ Silver Edition) were used to collect digital video of the trials in the sagittal and frontal planes with respect to the subject's direction of skating. All kinematic data were captured and processed using Vicon Nexus 2.2.1.

The subjects wore tight fitting compression clothing, so that the passive reflective markers would be placed as closely as possible to the anatomical landmarks. Sixty-seven passive reflective markers were affixed to the subjects' clothing with two-sided tape (Fig. 1). The marker set-up for the pelvis and legs were based on that of Collins et al. [40], the thoracic marker system was based on Leardini et al. [41] and the foot marker system was based on Leardini et al. [42]. Clusters of four non-collinear markers were positioned bilaterally on the upper arm, forearm, thigh and shank. There were also single markers placed on the spinous process of the seventh cervical and second thoracic vertebra, midpoint between the inferior spines of the scapula, jugular notch, xiphoid process, acromion processes, medial and lateral humeral epicondyles, styloid processes of radius and ulna, posterior superior iliac spines, anterior superior iliac spines, greater trochanters, medial and lateral femoral epicondyles, tibial tuberosities and femoral heads. Additionally, there were five markers permanently attached to each of the skates, in addition to one calibration marker. The skate markers were approximately over the posterior calcaneous, lateral and medial malleoli, first and fifth metatarsal heads and the distal toe. Four markers on the instrumented hockey stick were placed in a non-collinear pattern along the shaft (2), at the hosel and blade. Each marker was reinforced with tape to prevent it from falling off during the data collection and the plastic clusters were attached with neoprene straps and reinforced with tape. Due to the markers, participants were not allowed to use their personal skates.

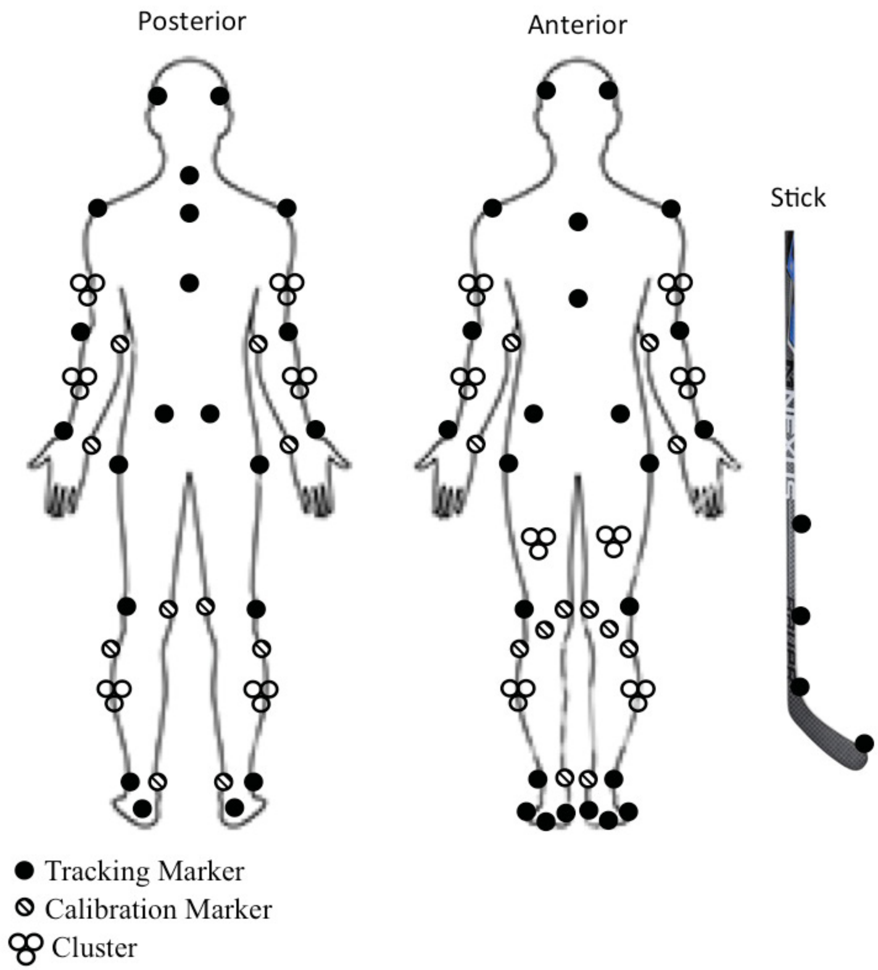

Fig. 1: Representation of the 81 spherical, retro-reflective markers placed on the upper and lower limbs, pelvis, trunk, hockey skate and hockey stick.

Experimental Protocol

Prior to the on-ice data collection, the subjects performed the Y-Balance Test as a measure of balance, lower limb strength and range of motion. The Y-Balance Test is a modified assessment of dynamic postural stability, comparable to the Star Excursion Balance Test [43]. Subsequently, they performed three single leg-standing long jumps as an estimate of functional unilateral leg strength. The strength and lower limb range of motion was evaluated using off-ice tests to remove them as a covariate effect in the analysis. By examining any sex differences on these variables, we could focus on the kinematics of skating. Then subjects changed into tight fitting compression clothing and test hockey skates (Bauer Hockey, Vapor 1X Model) provided. The same experimenter administered the off-ice tests and applied the markers to the subjects (Fig. 1) to ensure consistency across subjects. In order to compensate for the difference in height between the male and female groups, the jump length values were normalized by subject's height. Both the scores on the jump test and Y-Balance test were taken from the average of three trials performed by the subjects.

Subjects were given five minutes to warm-up on the ice (adjacent to the calibrated capture area), to get accustomed to the instrumented hockey skates and ice surface. Subsequently, three static calibrations of five seconds each were captured with the subject in a T-pose and holding the hockey stick.

For the skating trials, participants were instructed to stand immediately next to the blue line on the ice an athletic ready position. They were instructed to perform a maximal effort sprint to the next blue line, a distance of 15.3 m. For the start, the participants had to keep their feet parallel, facing the direction of motion and could not cross one skate over the other. Each subject performed five skating starts and continued forward acceleration sprints. The capture volume allowed the researchers to capture the first seven steps of the acceleration (Fig. 2). The participants skated with a hockey stick, and instructed to skate with the stick as they normally would during a game. They were able to choose from two different lengths of stick.

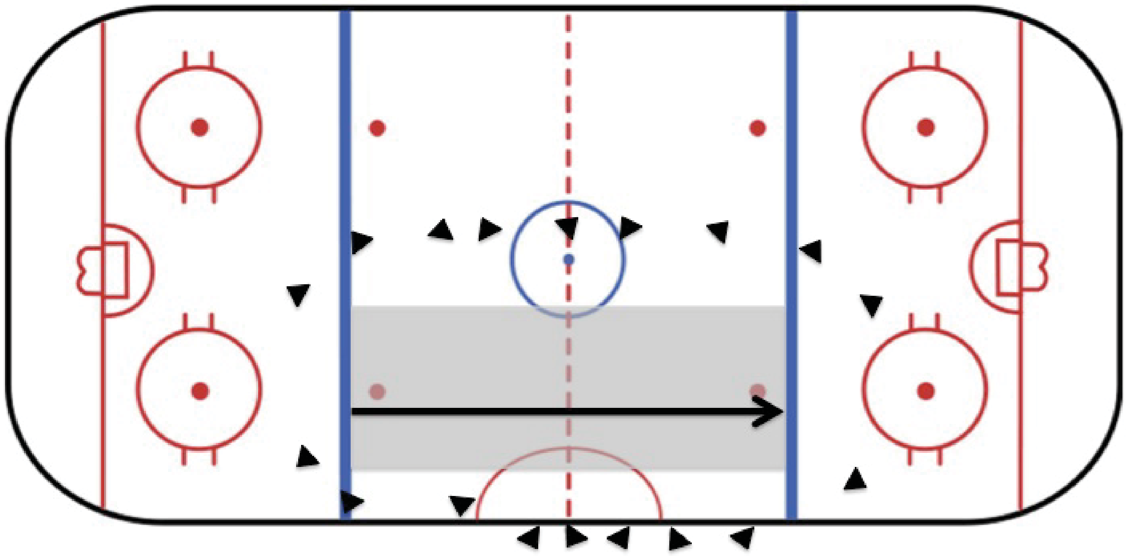

Fig. 2: Schematic representation of the on-ice Vicon camera set-up. Cameras are represented by the black triangles, with the approximate capture volume highlighted in grey. The black arrow indicates the direction of skating for the trial.

Data Analysis

The motion capture data were processed using Vicon Nexus 2.2.1. For the static calibration and skating trials, each trial was fully labeled and gap filled using the software using a combination of rigid body modeling and Woltring function. A 4^{th} order Butterworth filter with a cutoff frequency of 8Hz was used to smooth the data. In order to evaluate the kinematic and spatiotemporal variables throughout the skating task, locomotion events were detected using Visual 3D software (Ver 5.01.23, C-Motion, Germantown, Maryland, United States). Each skating trial collected was manually inspected in Visual3D to ensure that the algorithm had correctly identified the stride events. Based on previous work by our group [31], the method of Hreljac and Marshall (2000) was used to automatically detect the skate ON and OFF events, for the first seven steps. According to this algorithm, skate ON ice placement occurs at the moment of maximum acceleration of the heel marker in the horizontal direction and skate OFF occurs at the local maximum vertical acceleration for the toe marker [44]. These ON and OFF events allowed for calculation of spatiotemporal events, kinematic parameters and velocity, as well as identification of the step number during the acceleration phase of skating. All data were analyzed using custom-made MATLAB scripts (Mathworks, Natick, MA, USA) [45].

Using the MATLAB script, the most representative skating trial for each participant was determined according to Dixon et al. [46]. This approach allows for a captured trial to be used for data analysis, rather than the mean of several trials. The calculation involves calculating the root mean squared error between each curve and the mean curve for all dependent variables and selected the actual trial that is closest to mean for that participant.

Each subject's representative trial was visually inspected to identify the first step leg from the static start, such that the data were divided to either Step 1 Leg" or "Step 2 Leg". "Step 1 Leg" refers to the leg side that first stepped forward (regardless of whether this was the right or left leg of the subject). The "Step 2 Leg" refers to the contralateral side.

The skate ON and OFF events of that stride delimited the Stance phase. However, we also included a Stance 0 phase, which occurs from the beginning of the trial, to the skate OFF event for the Step 2 leg. This corresponds to the push-off phase of the Step 2 Leg. This phase was included because this initial push phase contributes to the skating acceleration start [23].

Statistical Analysis

Statistical analysis was performed using SPSS Statistics (IBM Corporations, Somers, U.S.A., Version 19.0). A mixed-ANOVA was used for each kinematic variable, to perform test for interactions between skater SEX and STEP NUMBER, as they accelerated. Group means and standard deviations were calculated for all variables. Normality of the data was tested using Kolmogrov-Smirnov Test and sphericity was tested using Mauchly's Test. Significant level for all tests was set at $p < 0.05$.

Results

The off-ice tests used were performed to measure leg strength and balance. From the jump distance measures in meters, there were significant differences between the single leg jump distance on the right ($p < .015$) and left ($p < .000$) between female and male subjects. However, when the jump distances were normalized to body height, the right jump distance was no longer significant, however the left jump distance remained significant ($p < .001$). The Y-Balance test was used as a proxy measure of strength and proprioception. The Composite Reach Distance score is calculated from the distance reached in three directions (anterior, posterior-medial and posterior-lateral) over the limb length of the participant. There were no significant differences between the scores on the right and left sides between female and male participants. As the posterior-medial reach most closely resembles a hockey stride motion, this reach distance was analyzed as well. There was no significant difference between the sexes (Table 2).

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 = .015 *
Single Leg Jump Right Normalized (%)	1.04 ± 0.07	1.14 ± 0.16	p = .115
Single Leg Jump Left (m)	1.77 ± 0.14	2.17 ± 0.21	p = .000 *
Single Leg Jump Left Normalized (%)	1.03 ± 0.07	1.20 ± 0.12	p = .001 *
Right Composite Reach Distance	131.26 ± 9.99	133.04 ± 8.77	p = .686
Left Composite Reach Distance	130.05 ± 8.91	134.05 ± 7.58	p = .310
Right Posterior-Medial Reach Distance	124.15 ± 11.50	129.83 ± 12.70	p = .320
Left Posterior Medial Reach Distance	122.85 ± 8.42	130.28 ± 8.93	p = .079

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

The performance, spatiotemporal and kinematic variables were calculated from the static start until the seventh step (Table 3). The males had a significantly greater maximum speed than female subjects (p <.000). However, when the maximum speed was normalized to body height the significant differences disappeared (p >.05). The females took significantly (p <.031) longer to complete the task than the male subjects and this remained significant (p <.023) when the task completion time was normalized to the distance skated to achieve the seven steps. At the seventh step, the females had covered an average of 13.28m, compared to 13.43m for the males, a difference that was not significant (p >.05).

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

Parameter	Female (Mean ± SD)	Male (Mean ± SD)	P-value
Peak Speed (m/s)	6.95 ± 0.31	7.60 ± 0.23	p = .000 *
Peak Speed Normalized (%)	4.06 ± 0.29	4.20 ± 0.23	p = .283
Task Completion Time (s)	1.97 ± 0.17	1.82 ± .12	p = .031 *
Task Completion Time Normalized (%)	0.15 ± 0.01	0.13 ± 0.01	p = .023 *
Distance Covered in 7 Steps (m)	13.28 ± 1.70	13.43 ± 1.46	p = .845

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

The male skaters had significantly wider steps at steps 1 (p<0.000), 2 (p<0.000), 4 (p<0.014), and 6 (p<0.000), even when the distance was normalized to body height (Table 4 and Fig. 3). Step width was calculated as the distance from ipsilateral proximal foot to contralateral proximal foot, which is perpendicular to the direction of primary motion. However, the normalized stride length did not differ between the sexes (Table 5). For Tables 4 and 5, the pairwise comparisons were performed between the male and female subjects at each step.

Table 4: Average Stride Width (Mean ± SD) for Step 1-7 of Skating Acceleration

Parameter	Gender	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6
Step Width (m)	Female	0.15 ± 0.07	0.05 ± 0.03	0.05 ± 0.04	0.07 ± 0.07	0.10 ± 0.08	0.05 ± 0.04
	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 =.000 *	p=.000 *	p =.066	p=.008 *	p =.054	p=.000 *
Step Width Normalized (%)	Female	0.09 ± 0.04	0.03 ± 0.02	0.03 ± 0.02	0.04 ± 0.04	0.06 ± 0.05	0.03 ± 0.02
	Male	0.18 ± 0.05	0.10 ± 0.04	0.05 ± 0.03	0.09 ± 0.04	0.10 ± 0.05	0.10 ± 0.04
	P-value	p =.000 *	p =.000 *	p =.103	p =.014 *	p =.085	p =.000 *

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

Table 5: Average Stride Length (Mean ± SD) for Stride 1-5 of Skating Acceleration

Parameter	Gender	Stride 1	Stride 2	Stride 3	Stride 4	Stride 5
Stride Length (m)	Female	1.19 ± 0.27	2.26 ± 0.32	2.67 ± 0.38	3.07 ± 0.41	3.39 ± 0.41
	Male	1.93 ± 0.23	2.27 ± 0.24	2.67 ± 0.29	3.07 ± 0.36	3.50 ± 0.40
	P-value	p =.746	p =.979	p =.984	p =.996	p =.601
Stride Length Normalized (%)	Female	1.10 ± 0.15	1.32 ± 0.17	1.55 ± 0.18	1.79 ± 0.20	1.98 ± 0.18
	Male	1.06 ± 0.12	1.25 ± 0.14	1.47 ± 0.14	1.69 ± 0.17	1.93 ± 0.19
	P-value	p =.537	p =.368	p =.302	p =.286	p =.576

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

For the kinematic data, the maximum, minimum and range of motion angles were calculated for all stance phases (0-6) for hip flexion/extension, hip adduction, abduction, hip internal/external rotation, and knee flexion/extension. For ankle flexion/extension, stance phases 0-5 were analyzed to do an artifact in the data for stance 6, which prevented stance 6 from being analyzed. The average hip kinematic data is in Table 6 and average knee and ankle data is in Table 7.

Table 6: Average Hip Kinematic Variables (Mean ± SD) for Stance Phases 0-6

Stance Phase	Sex	Hip Flexion/Extension Angle (deg.)			Hip Abduction/Adduction Angle (deg.)			Hip Internal/External Rotation Angle (deg.)		
		Max.	Min.	ROM	Max. *	Min. *	ROM	Max.	Min.	ROM
0	Female	35.1 ± 13.3	-5.8 ± 6.3	40.9 ± 11.1	-7.2 ± 5.6	-18.2 ± 5.0	11.0 ± 4.0	-5.8 ± 11.3	-20.4 ± 11.6	14.6 ± 6.2
	Male	33.9 ± 23.9	-5.7 ± 11.7	39.6 ± 22.0	-9.8 ± 8.7	-22.5 ± 9.4	12.7 ± 7.1	-5.6 ± 12.5	-24.5 ± 13.5	18.9 ± 8.6
1	Female	52.8 ± 14.2	-4.8 ± 8.2	57.6 ± 8.6	-5.5 ± 3.4	-18.5 ± 4.2	13.0 ± 5.1	8.0 ± 16.6	-13.8 ± 15.3	21.7 ± 7.5
	Male	41.4 ± 11.0	-8.8 ± 10.2	50.3 ± 12.0	-7.1 ± 4.9	-24.4 ± 6.4	17.3 ± 6.6	-10.9 ± 10.4	-28.7 ± 13.0	17.8 ± 6.9
2	Female	55.3 ± 10.0	-6.7 ± 7.1	62.0 ± 9.7	-2.3 ± 4.3	-15.3 ± 4.5	13.1 ± 5.0	4.0 ± 13.3	-14.1 ± 12.5	18.1 ± 7.0
	Male	53.7 ± 15.0	-10.4 ± 9.8	64.0 ± 17.8	-8.9 ± 6.7	-24.8 ± 9.9	15.9 ± 10.7	4.2 ± 9.7	-20.2 ± 16.8	24.4 ± 15.1
3	Female	60.4 ± 10.1	-5.8 ± 8.0	66.2 ± 6.1	-2.3 ±3.8	-19.5 ± 3.1	17.2 ± 5.3	11.8 ± 14.0	-10.9 ± 14.9	22.7 ± 6.9
	Male	59.8 ± 5.9	-12.7 ± 9.0	72.4 ± 11.9	-8.5 ± 2.3	-23.9 ± 6.8	15.5 ± 5.3	-0.9 ± 6.4	-21.8 ± 11.3	21.7 ± 10.2
4	Female	59.9 ± 8.2	-6.7 ± 8.1	66.6 ± 9.9	-1.4 ± 5.1	-18.8 ± 5.0	17.4 ± 5.7	7.0 ± 15.4	-15.8 ± 19.7	22.8 ± 11.3
	Male	61.0 ± 13.1	-10.3 ± 11.3	71.3 ± 9.8	-9.3 ± 1.6	-24.6 ± 6.4	17.8 ± 6.8	6.0 ± 7.8	-19.4 ± 15.4	25.4 ± 11.1
5	Female	63.5 ± 9.0	-3.1 ± 14.3	66.5 ± 15.6	-0.9 ± 5.2	-23.6 ± 3.7	22.7 ± 5.2	15.2 ± 14.4	-13.0 ± 15.1	28.2 ± 10.8
	Male	66.3 ± 8.8	-12.4 ± 10.7	78.7 ± 9.8	-9.3 ± 1.6	-26.2 ± 5.4	15.8 ± 6.0	7.1 ± 8.0	-20.7 ± 11.5	27.8 ± 9.8
6	Female	64.9 ± 10.3	8.8 ± 10.9	56.1 ± 14.5	-0.3 ± 6.0	-19.5 ± 6.8	19.1 ± 7.0	10.9 ± 15.2	-7.8 ± 14.2	18.6 ± 8.3
	Male	69.2 ± 14.7	-2.1 ± 10.4	71.3 ± 11.1	-9.3 ± 6.0	-28.1 ± 6.3	18.9 ± 5.8	12.0 ± 9.0	-14.0 ± 15.0	26.0 ± 9.6

*Indicates significant main effect of sex for that dependent variable ($p < .05$)

Table 7: Average Knee and Ankle Kinematic Variables (Mean ± SD) for Stance Phases 0-6

Stance Phase	Sex	Knee Flexion/Extension Angle (deg.)			Ankle Flexion/Extension Angle (deg.)		
		Max.	Min.	ROM	Max.	Min.	ROM
0	Female	63.9 ± 6.2	22.5 ± 5.5 *	41.4 ±7.6	31.0 ± 5.3	-7.8 ± 3.9 *	38.8 ± 5.5 *
	Male	69.8 ± 16.2	29.8 ±9.1 *	40.0 ± 20.6	29. 2 ± 4.1	-1.1 ± 5.7 *	30.2 ± 8.2 *
1	Female	70.4 ± 6.2	23.2 ±5.2	47.3 ± 5.7	27.7 ± 2.1	-9.4 ± 4.8	37.1 ± 4.4
	Male	73.5 ± 9.0	22.5 ± 5.7	51.0 ± 10.2	28.7 ± 4.0	-6.4 ± 4.3	35.2 ± 3.3
2	Female	70.4 ± 7.1	21.6 ± 5.6	48.7 ± 9.7	28.8 ± 3.7	-8.2 ± 5.1	37.0 ± 5.0
	Male	73.6 ± 9.4	22.1 ± 5.8	51.5 ± 10.4	25.7 ± 5.2	-8.3 ± 6.7	33.9 ± 4.8
3	Female	75.1 ± 8.0	24.2 ±3.8	50.9 ± 5.7	29.0 ± 4.6	-8.9 ± 4.0	38.0 ± 6.1
	Male	78.8 ± 12.0	21.6 ± 8.8	57.2 ± 12.7	28.9 ± 5.4	-8.9 ± 3.9	37.7 ± 3.6
4	Female	74.1 ± 5.7	19.3 ± 5.6	54.8 ± 8.3	27.8 ± 4.1	-10.4 ± 6.1	38.2 ± 4.7
	Male	82.3 ± 7.5	24.9 ± 7.9	57.4 ± 11.8	28.8 ± 2.3	-6.3 ± 5.8	35.0 ± 4.3
5	Female	76.8 ± 9.4	20.4 ± 5.2	56.5 ± 8.6	29.2 ± 5.0	-9.1 ± 7.8	38.4 ± 7.4
	Male	82.8 ± 11.3	18.5 ± 6.8	64.3 ± 14.0	25.6 ± 3.9	-9.7 ± 4.6	35.3 ± 3.3
6	Female	74.8 ± 4.8	25.2 ± 8.1	49.5 ± 8.1	24.5 ± 3.1	5.9 ± 10.4	18.6 ± 10.5
	Male	88.3 ± 6.7	25.8 ± 7.4	62.4 ± 8.7	26.5 ± 1.8	-0.9 ± 7.6	27.3 ± 7.2

*Indicates significant Sex*Stance interaction ($p < .05$)

There was a significant main effect of sex on frontal plane hip maximum angle (p<0.000) (Fig. 4, Panel A), such that across all steps, the female skaters had a more adducted hip position than the male skaters. Also, the minimum frontal plane hip angle was significantly different between sexes (p<0.006) (Fig. 4, Panel B).

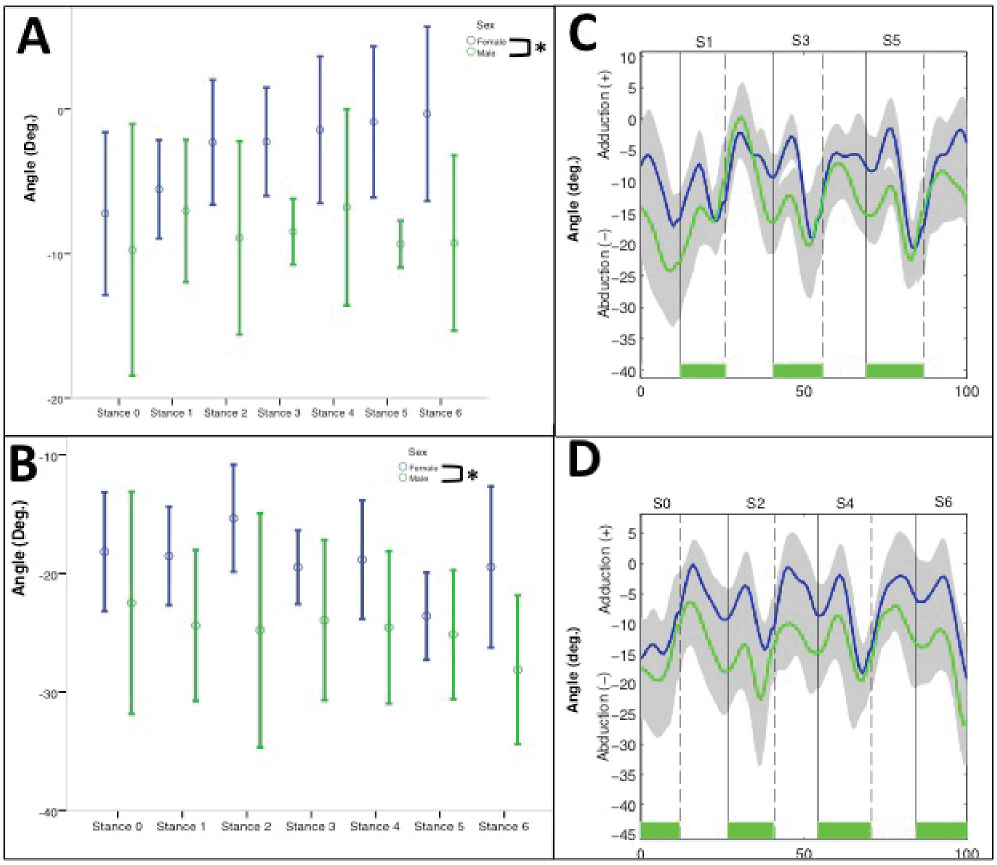

Fig. 3: Hip Kinematics (female-blue, male-green)
A: Average maximum hip angle for abduction-adduction by sex for stances 0-6 in C. There was a significant effect of sex (p<0.000).
B: Average minimum hip angle for abduction-adduction by sex for stance 0-6 in D. There was a significant effect of sex (p<0.006).
C: Average hip angle abduction-adduction by sex for Step 1 leg (± SD gray bands)
D: Average hip angle abduction-adduction by sex for Step 2 leg (± SD gray bands)
In Panels C and D, the horizontal green bars represent the stance phases (S0-S6)

There was a significant Stance*Sex interaction for sagittal plane knee minimum position (p<0.039) (Fig. 5, Panel A) and the knee angle at ice contact (p<0.037) (Fig. 6, Panel A). Post-hoc test revealed that the significant different for sagittal plane knee minimum position occurred during Stance 0 (p<0.047). Sex differences were observed for the knee angle at ice contact observed at Step 4 (p<0.016) and Step 6 (p<0.000).

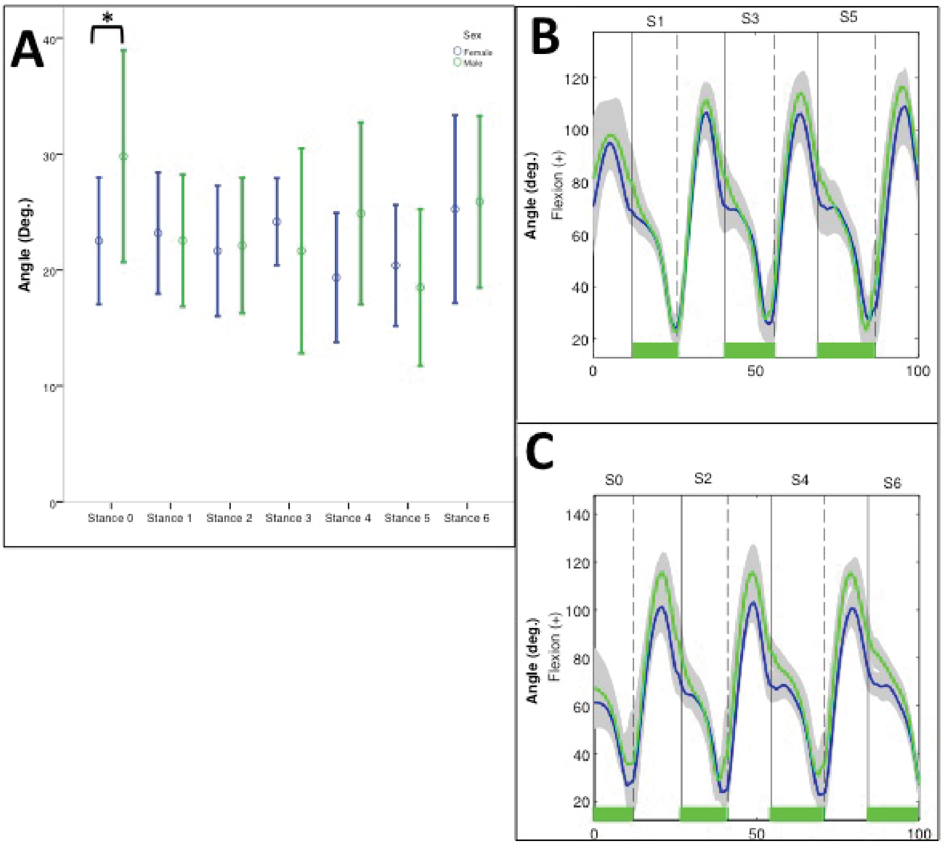

Fig. 4: Knee Kinematics (female-blue, male-green).
A: Average knee minimum flexion for the stance phases 0-6. There was a significant Stance*Sex interaction at Stance 0 (p<0.047).
B: Average knee flexion angle by sex for Step 1 leg (± SD gray bands)
C: Average knee flexion angle by sex for Step 2 leg (± SD gray bands)
In Panels B and C, the horizontal green bars represent the stance phases (S0-S6)

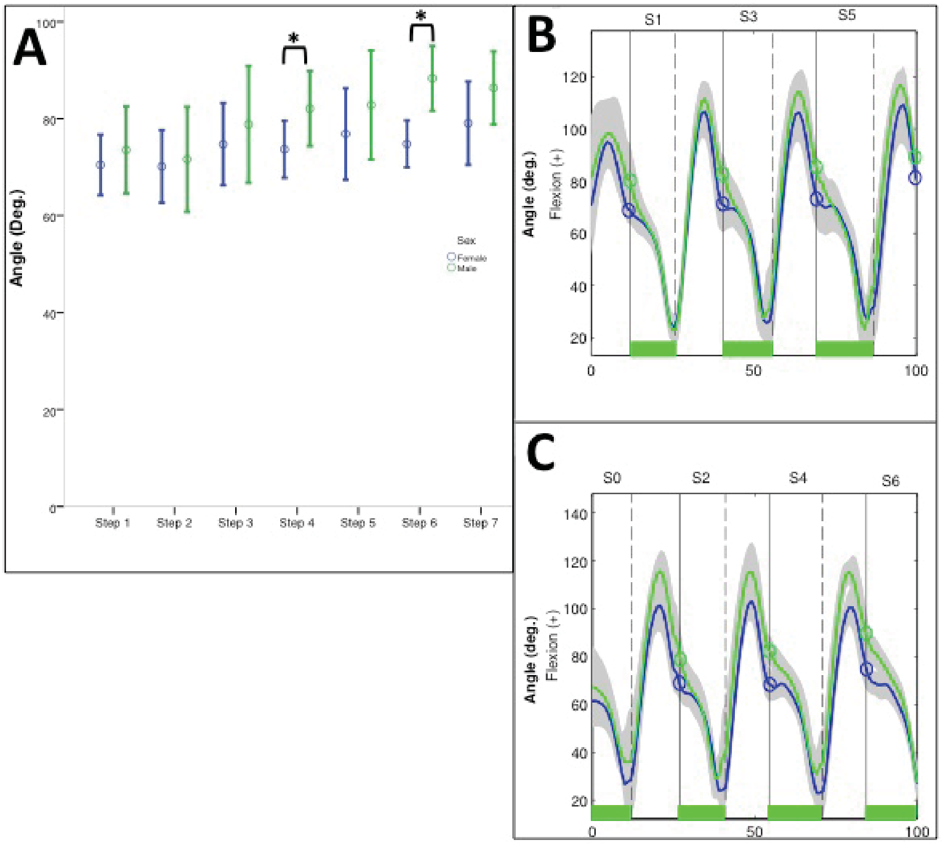

Fig. 5: Knee Kinematics (female-blue, male-green)
A: Average knee flexion angles at skate ON for the seven steps captured. There was a significant Stance*Sex interaction at Step 4 ($p<0.016$) and Step 6 ($p<0.000$).
B: Average knee flexion angle by sex for Step 1 leg (± SD gray bands)
C: Average knee flexion angle by sex for Step 2 leg (± SD gray bands)
In Panels C and D, the horizontal green bars represent the stance phases (S0-S6). The solid vertical lines represent the average skate ON events. The circles approximate where the data was extracted.

For the ankle kinematics, there were significant Stance*Sex interactions for sagittal ankle plantar flexion angle ($p<0.050$) (Fig. 6, Panel A) and ankle range of motion angle ($p< 0.007$) (Fig. 6, Panel B). Post-hoc tests revealed that the interaction took place during Stance 0 for both the ankle plantarflexion angle ($p<0.008$) and ankle range of motion ($p<0.015$).

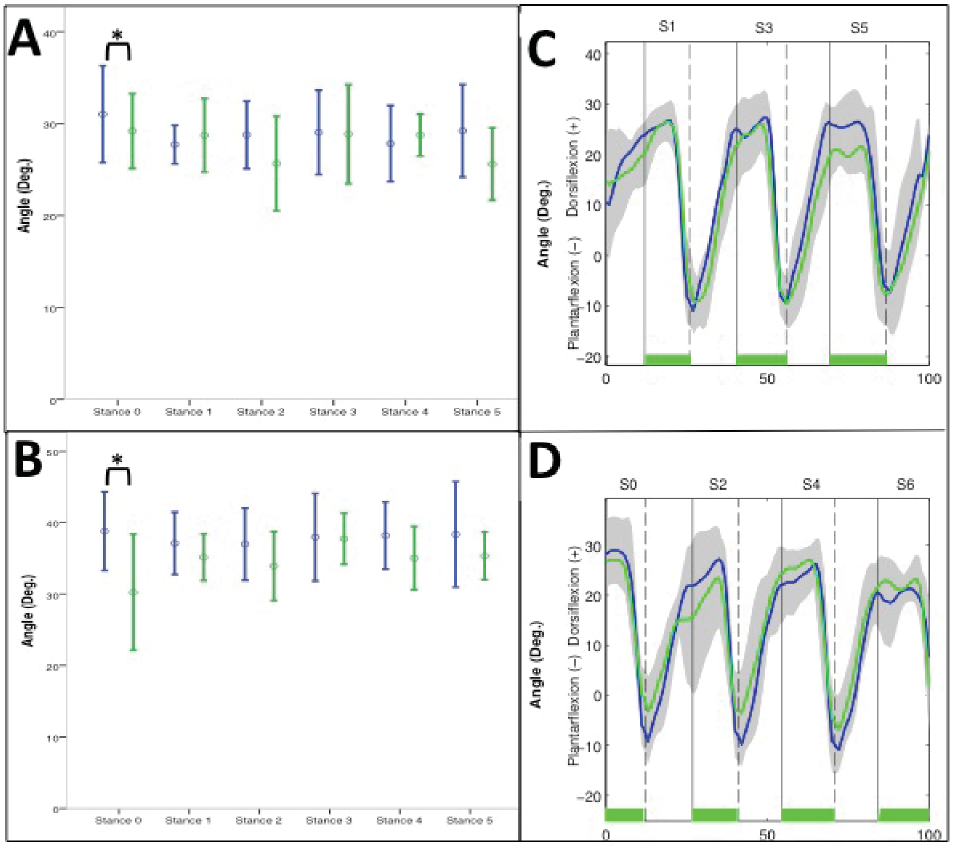

Fig. 6: Ankle Kinematics (female-blue, male-green)
A: Average ankle plantarflexion for the stance phases 0-5. There was a significant Stance*Sex interaction at Stance 0 (p<0.008).
B: Average ankle angle range of motion for each stance phase (0-5). There was a significant Stance*Sex interaction at Stance 0 (p<0.015).
C: Average ankle plantar-dorsi flexion by sex for Step 1 leg (± SD gray bands)
D: Average ankle plantar-dorsi flexion by sex for Step 2 leg (± SD gray bands)
In Panels C and D, the horizontal green bars represent the stance phases (S0-S6).

Discussion

The goal of this study was to conduct a three-dimensional kinematic analysis of the lower limbs of female and male ice hockey players during skating start acceleration. Quantitative measures of lower limb kinematics during skate contact and stance phases were calculated from motion capture data collected over 15 m surrounded by eighteen-cameras on an indoor arena ice surface. Bilateral kinematic measures were taken for the first seven steps (~3.5 strides) over a distance of 15 m. While the camera set-up and take down was an intensive and laborious process, this study represents a major achievement in the three-dimensional motion capture, as we were able to calibrate a large (15m*3m*2m) capture volume in the arena, to collect externally valid measures of on skating biomechanics.

Differences in the hip, knee and ankle kinematics were identified between elite male and female ice hockey players. While the off-ice tests indicated that the strength, balance and flexibility profiles were similar between the sexes (when normalized to body height), performance differences for on-ice variables, such as stride width, speed and task completion time were still detected between male and female skaters.

Unlike in running locomotion, there is more and persistent hip abduction and external rotation in skating, presumably to ensure an optimal push-off force can be generated by acutely angling the skate blade relative to the direction of movement. Throughout the skating acceleration, from a static start to the seventh step, regardless of sex, the hips were constantly abducted, to varying degrees. This positioning of the hip distinguishes skating locomotion from walking or running and supports theory on skating biomechanics [8].

As was hypothesized, there was a significant difference between the kinematics of the hip abduction/adduction between male and female hockey players. Throughout the skating acceleration, the female players were up to 10˚ less abducted at the hip than the males.

The values reported for hip abduction and adduction are inconsistent with those of Stull [23], however that study included only male youth hockey players as subject, and could help explain the inconsistencies. There were no differences in hip angular movement in either the sagittal or transverse planes. At ice contact, the male players had significantly more knee flexion at step 4 and 6. Upon visual inspection of the knee angle-time patterns, at ice contact, in general the female skaters exhibited a momentary knee extension cessation (or plateau), whereas the male skaters extend their knee throughout ice contact. As this study was the first to kinematic analysis of skating to include female subjects, it is the first to report this finding regarding knee extension in female skaters at ice contact.

As it has been established that the female pelvis anatomy differs from the male pelvis anatomy [36], one has to wonder how this would affect skating locomotion, which has much greater movement of the hip in the frontal plane compared to running [8, 12]. At ice contact, the female skaters had less hip adduction and the momentary cessation of knee extension. We hypothesize that for female athletes this may be a habitually learned protective mechanism so as to avoid high valgus moments and excessive strain to the medial tensile connective structures of the knee. In a study comparing jump biomechanics of female and male dancers and team sport athletes, female team sport athletes exhibited the highest peak knee valgus of the groups studied [47]. In soccer, basketball and US Naval Academy athletes, female athletes have an established higher risk of non-contact knee injuries [48]. It is postulated that biomechanics play a role in this phenomenon, however, more studies in female hockey players, are needed to study this in greater detail.

One of the performance outcomes that differed significantly between the sexes was the step width, both normalized and absolute values. This could possibly relate to the significant differences in hip abduction; males were ~10° more abducted, allowing the foot to extend more laterally, thereby allowing greater step width than female skater, which is inconsistent with the similar male to female estimates from the Y-Balance posterior-medial direction test. The stride length (absolute and normalized) did not differ significantly between the male and female skaters. In Renaud et al. (2015), the cohort studied was entirely male, but they were divided among high and low caliber hockey players. Contrary to their hypothesis, the high and low caliber skaters have a similar average stride width [31]. This supports our hypothesis that there are subtle yet significant differences in the skating biomechanics of female and male ice hockey players due the differences in hip anatomy.

Comparing the results of our off-ice tests to previous work, our subjects outperformed those in Barber et al. [49] study on sports activity level and jump performance. In the one-legged standing long jump, our elite female athletes jumped on average 49% further, while the male athletes jumped 16% further than previously reported high-level athletes [49]. There was a significant difference in strength estimates between our female and male cohorts based on absolute jump length measures. However, when the jump distances were normalized to player height, the right side was no longer significant, but the left leg jump distance remained significant between male and female athletes. This curious result is difficult to explain. Because we did not capture any kinetic data, it is unknown how this affected the performance outcomes and kinematics.

Maximum speed was another performance outcome that was studied. The average male peak speed was significantly higher than the average female peak speed, however, when these values were normalized to body height, this speed difference disappeared. During the Stance 0 phase, when the Step 1 leg is in its swing phase, and the Step 2 leg is pushing off the ice, the male skaters had significantly more knee flexion and more ankle dorsiflexion than the female skaters. This starting position may be increasing the propulsive force generated form the static start and translate to an increase in skating speed for the male skaters. Our proxy measure of leg strength, the standing long jump, showed similar values between the sexes. However, there are gross differences between the sexes during the dynamic skating movement. The difference in knee flexion at ice contact may be affective the propulsive force generated. Also, as the females plateau during knee extension at contact, they may generate less net propulsive power due to inhibited quadriceps contraction. A similar study design using EMG is warranted to substantiate these claims.

Renaud et al. [31] is the only other study to capture three-dimensional kinematic data on the ice surface to our knowledge. However, they had a ten-camera set-up and were only able to capture the first four steps of acceleration [31], therefore, we are unable to compare our peak speed values to theirs. To date, the only other study to capture on-ice biomechanics data in hockey players is Buckeridge et al. [34], which measured skating over 30m [34]. They did not measure the peak velocity over the first six strides, so there is no comparable data to our peak speed values.

While Abbott [37] claimed that forward skating biomechanics are the same for both male and female hockey players. In general, from our data gross movement patterns between the male and female high calibre ice hockey skaters are similar; however, as noted already, significant sex differences in hip abduction and knee flexion patterns were shown in terms of forward skating start and acceleration. Abbott's claim is not support by our empirical data.

There are many implications of this study. To our knowledge, this is the first study to include a cohort of elite female hockey players in an analysis of skating biomechanics. As women's hockey as increased in popularity, researchers have called for more inclusion of female subjects in studies on hockey performance. Secondly, this study built upon the foundation laid by Renaud et al. [31] and their successful use of three-dimensional motion capture on an actual ice surface [31]. By increasing the quality of the cameras and doubling the number of cameras, we were able to double the length of the capture volume and collect data on the first seven steps of skating acceleration. Since there are now multiple studies demonstrating the feasibility of on-ice motion capture [31, 33, 34], future studies on skating biomechanics should be performed in the arena and should study more complicated tasks, such as backwards skating, puck handling, shooting and steady-state skating.

With respect to practical implications, this study raises numerous issues related to coaching and injury rehabilitation. Traditionally, young male and female hockey players are taught the same skating techniques. However, the results of this study, and future research, may lead to some sex-specific skating technique instructions, due to the kinematic differences observed between the male and female skaters. Furthermore, rehabilitation professionals should take these results into account when planning a rehabilitation program for ice hockey players. Due to the subtle yet distinct differences in hip and knee anatomy, rehabilitation for hip and groin injuries may need to differ for male and female ice hockey players. With the established risk for knee injuries in female athletes [48], intervention training for females that focus on hip and knee landing and propulsion mechanics may be warranted to reduce the incidence of knee injuries.

Conclusion

This study was the first on-ice analysis of skating biomechanics to include high caliber male and female ice hockey players. Using a state-of-the-art three-dimensional motion-capture system directly on the ice surface, we were able to capture the first seven steps of skating acceleration with a whole-body marker set-up. This achievement builds upon previous research and demonstrates the feasibility of collecting externally valid data in the arena setting. As expected, there were kinematic differences at the hip between the male and female subjects. With respect to hip abduction and adduction, throughout the skating acceleration, all participants' hips were consistently abducted. However, the female skaters were significantly less abducted than their male counterparts. Furthermore, the females' knees were more extended at ice contact. For the initial propulsive push-off, the male skaters demonstrated more knee flexion and more ankle dorsiflexion, which may lead to a more powerful skating start. The males achieved a significantly higher peak speed and significantly lower task completion time than the female skaters. The male skaters had a significantly wider skating step, which could not be attributed to the limb length or leg strength, as the two cohorts had a similar profile. Further on-ice research is warranted to continue studying more complex skating skills, in both male and female subjects.

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Conclusion

This study contributes to the growing literature that has used three-dimensional motion capture technology in an externally valid field setting, rather than being restricted to a laboratory. Collecting data on skating biomechanics from an arena is more advantageous than being in the laboratory because the movement of the subjects is not restricted by a confined laboratory space and the skating style of the subjects is not affected by frictional differences due to the artificial ice. Despite objections to the use of passive motion capture cameras in an arena [26], this study builds upon the work of Reanud et al. [31], and shows that this technologies need no longer be restrained to laboratory use [31]. We were able to calibrate a volume that captured the first seven steps of skating acceleration, using a full-body marker set-up.

Biomechanical differences between males and females have been well documented in running [36], soccer and basketball [48]. Based on our results, there would appear to be biomechanical differences, mostly at the hip, between male and female ice hockey players. Future research could help clarify the biomechanical differences between male and female ice hockey players. This could help establish new skating parameters for coachers and trainers, as current skating training is largely based on abstract qualitative information. This study is the first detailed quantitative study of lower limb kinematics in females and males during skating. Therefore, coaches and trainers can reference this information and performance variables when designing their coaching tools. With respect to the female skaters, future research and coaching should investigate implementing intervention strategies to reduce knee injuries, as has been done in soccer and basketball [7]. Furthermore, this could have implications for rehabilitation professionals, due to the established differences in knee injury risk [48]. Finally, these findings could have implications for ice hockey equipment manufacturers. Traditionally, equipment and ice skates have been manufacturer as "unisex" with no different female-specific options for players. However, based on our results, there is reason to consider making female-specific equipment, due to the differences in skating technique. Two possibilities for this equipment would include a hockey pant that is designed for the way the female hip and pelvis moves during skating and would not restrict their range of motion, if this were the case. Also, most of the female participants were wearing kids' sized skates, as skates are currently manufactured in a unisex design and separated into adult (size 6 and above) and kids (size 5.5 and below). The kids skates do not have the same rigidity and construction of the adult skate, so it could help the female players if they had access to a smaller, but durably built skate, similar to that of their male counterparts.

There are some weaknesses to the current study. While the study detailed the kinematics of the lower limbs in both male and female ice hockey players, it is lacking information about the upper limbs and a whole-body analysis of skating. This information from this study provides a solid foundation with respect to skating biomechanics; however, it is not known how this information can be directly extrapolated to the context of a hockey game.

This study provides empirical data on biomechanical differences in ice-skating between male and female ice hockey players, which provides novel information to this research field. Future avenues for on-ice kinematic research should include other skating maneuvers, like skating at full-speed, with a puck and performing game-like scenarios. Furthermore, other technologies, such as Inertial Measurement Units could be examined as another tool to be used.

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Appendices

Appendix A: Consent Form

INFORMATION AND INFORMED CONSENT

Investigator: Jaymee R. Shell , M.Sc. candidate, jaymee.shell@mail.mcgill.ca
David J. Pearsall, PhD, supervisor, david.pearsall@mcgill.ca
McGill Ice Hockey Research Group, Department of Kinesiology and Physical Education, McGill University
Research funded by: National Science and Engineering Research Council (CR DPJ 45 3725-13) and Bauer Hockey Corp.

Title of Project: Three-dimensional kinematics of the lower limbs and trunk in elite male and female ice hockey players performing a skating and acceleration task

McGill IRB II File Number: 463-0515

Statement of Invitation

You are invited to participate in a research project conducted by the above named investigators. This research project will be performed at the Ed Meagher Arena, 7200 Sherbrooke West, Montreal, Quebec, H4B 1R2. You are asked to come to one experimental session that will last up to one and a half hours. To qualify for this study, participants must not presently have any lower limb injuries or any that have prevented them from playing ice hockey within the past year.

Purpose of the Study

The purpose of this study is to conduct a three-dimensional kinematic motion analysis of ice hockey forward skating start and strides on the actual ice surface; and to compare the movement patterns of elite male and female ice hockey players. Specifically, we will be comparing the differences, if any, in velocity, lower limb (hip, knee, ankle) range of motions, and skate/ice orientations between the male and female subjects. This research is being conducted as part of a master's thesis project and its findings will be disseminated in the final thesis report, along with research publications and conference presentations.

Your participation in this study involves:

1. Providing informed consent prior to experimental participation.
2. Providing data concerning your physical attributes (weight, height, age, and different body segment measurements).
3. Perform three maximal vertical jumps and three one legged jumps on each leg
4. Placing 26 passive reflective makers on various anatomical landmarks

5. Skating through the motion capture area (calibration, followed by data collection)

The data collection period will be videotaped, using two Go Pro cameras. These videos will be used by the researcher and may be added into public presentations. In this situation, the identity of the participant will be protected, such that faces will be blurred and identifying features will be obscured. Furthermore, the subject's name will not be used in the presentation.

Risks and Discomforts

It is anticipated that you will encounter no significant discomfort during these experiments. You will be required to wear tight fitting athletic clothing during the experiment. Redness and itchiness from the double-sided adhesive tape used to affix the reflective markers to your skin will be temporary and short lived if experienced at all.

Benefits

Participants will receive a 25$ gift certificate for participating in the study.

Confidentiality

All of the personal information collected during the study concerning you will be numerically encoded based on the order of testing in order to keep your identity confidential. These records will be maintained in a locked cabinet at the Biomechanics Laboratory, McGill University by Dr. David Pearsall for five years after the completion of the project, and will be destroyed afterwards. Only those listed on the consent form will have access to them. For presentation and publication purposes, you will remain entirely anonymous.

Inquiries Concerning this Study

If you require information concerning the study (experimental procedures or other details), please do not hesitate to contact Jaymee Shell, jaymee.shell@mail.mcgill.ca or Dr. David Pearsall, david.pearsall@mcgill.ca

Responsibility clause

In accepting to participate in this study, you will not relinquish any of your rights and you will not liberate the researchers nor their sponsors or the institutions involved from any of their legal or professional obligations.

Consent

Please be advised that your participation in this research undertaking is strictly on a voluntary basis, and you may withdraw at any time. A copy of this form will be given to you before the end of the experimental session.If you have any questions or concerns regarding your rights or welfare as a participant in this research study, please contact the McGill Ethics Officer at 514-398-6831 or lynda.mcneil@mcgill.ca.

Signatures

Please sign below once you have read the consent document, had all your questions answered and only if you agree to participate in this study on a voluntary basis. Note all participants must be 18 years of age or older.

Signature: ______________________________

Date: ______________________________

Appendix B: Questionnaire

PRE-SCREENING QUESTIONNAIRE

Name: ______________________________

Date of Birth: ______________________________

Sex: ______________________________

Hockey Experience (years): ______________________________

Highest Level Played: ______________________________

Current Team: ______________________________

Skate Size: ______________________________

Skate Model: ______________________________

Shot Handedness: ______________________________

Dominant Leg (kick a ball): ______________________________

Hand that you write with?: ______________________________

---

1. In the past year have you suffered any injuries to your hip, knee, or ankle? Has it prevented you from playing hockey? Please explain.

   ____

   ____

   ____

2. In the past year have you experienced any other lower body injuries? (E.g. broken bones, torn ligaments, etc.) Have they prevented you from playing hockey? Please explain.

   ____

   ____

   ____

3. In the past year have you suffered any nervous system injury? (E.g. Concussion, damage to a nerve, numbness or pins and needles, etc.) Has it prevented you from playing hockey? Please explain.

____

____

____

4. Is there any other reason why you believe you shouldn't participate in this study? Please explain.

____

____

____

Off-Ice Testing

Star Excursion Balance Test

For left support leg, right reaching leg:

Trial	Direction of Reach							
	A	AM	M	PM	P	PL	L	AL
1								
2								
3								

For right support leg, left reaching leg:

Trial	Direction of Reach							
	A	AM	M	PM	P	PL	L	AL
1								
2								
3								

Vertical Jump

Trial	Jump Height
1	
2	
3	

1-Legged Jump

Trial	Jump Height
Right-1	
Left-1	
Right-2	
Left-2	
Right-3	
Left-3	