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Three-dimensional kinematics of the lower limbs during forward ice hockey skating

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Abstract
The objectives of the study were to describe lower limb kinematics in three dimensions during the forward skating stride in hockey players and to contrast skating techniques between low- and high-calibre skaters. Participant motions were recorded with four synchronized digital video cameras while wearing reflective marker triads on the thighs, shanks, and skates. Participants skated on a specialized treadmill with a polyethylene slat bed at a self-selected speed for 1 min. Each participant completed three 1-min skating trials separated by 5 min of rest. Joint and limb segment angles were calculated within the local (anatomical) and global reference planes. Similar gross movement patterns and stride rates were observed; however, high-calibre participants showed a greater range and rate of joint motion in both the sagittal and frontal planes, contributing to greater stride length for high-calibre players. Furthermore, consequent postural differences led to greater lateral excursion during the power stroke in high-calibre skaters. In conclusion, specific kinematic differences in both joint and limb segment angle movement patterns were observed between low- and high-calibre skaters.

Keywords: *Ice hockey, kinematics, lower limbs, skating*

Introduction

Ice hockey is a fast-paced sport requiring excellent physical conditioning, as well as precision and control of technical skills such as shooting, passing, and a variety of skating skills. Forward skating in hockey is the fundamental movement pattern for most skating tasks. Well-developed hockey skating technique allows players to move quickly and accurately on the ice. Proficiency in this movement allows players both to compete effectively for possession of the puck as well as to attend to strategic tasks in the game. Effective and efficient competition for the puck then increases the likelihood of scoring, which is the objective of the game. Although skating development emphasizes good skating technique, rarely is it assessed objectively. To quantify technique, kinematic measures are necessary. However, given the dynamics of the sport, the unique conditions of the task, and a general lack of interest in studying the sport, obtaining these measures has been elusive. Many systems used to measure kinematic data, such as the Optotrak® and MotionStar® systems,

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use active markers and require participants to be tethered to a personal computer for data logging, which is impractical for such a dynamic task as ice hockey skating. Passive marker systems such as the Vicon© motion capture system also have limited applications for the collection of kinematic data in a field setting, or hockey arena in this case. The dynamics of the hockey skating task would require many cameras to be present to capture all of the passive markers on the skater as they cover large distances on-ice. Notwithstanding the cost of using such a system, controlling ambient lighting in such a large environment would be difficult. Furthermore, collection of kinematic data on-ice requires calibration of a relatively large volume, which may introduce measurement error. Lafontaine and Lamontagne (2003) proposed using a moveable, two-camera system to record three-dimensional kinematics of hockey skating. The cameras are mounted on a cart, which travels on a fixed track parallel to the direction of movement of the skaters. Although the proposed system produced relatively small (3.6–5.5%) errors in a controlled laboratory setting, the system has various limitations, In laboratory tests, skating motion was not accurately simulated, and therefore transferability between this experimental task and human motion during the skating stride is debatable. This mobile data acquisition system allows only for analysis of one side of the body during a linear motion. This is problematic, as asymmetries between limbs have been shown to exist in many tasks. Thus, minimal factual information on forward skating technique exists.

Kinematics of forward skating would describe the linear and angular motions of the body during a stride. A skating stride is biphasic and consists of support and swing phases. The support phase can be further divided into single and double support (18% and 82% of support phase respectively) (Marino, 1983; Pearsall, Turcotte, and Murphy, 2000). Propulsion takes place during both double and single support during the outward rotation of the thigh, coinciding with initial extension of the hip and knee (Pearsall et al., 2000).

Players of a low calibre (low skill, standard of play, and league of play) seem, by observation, markedly different than those of high calibre or professional players, especially to the trained eye of an experienced coach. However, describing these technique differences precisely is complex. Several researchers have attempted to do so. For example, McCaw and Hoshizaki (1987) evaluated skating kinematics using two-dimensional filming of three athletes. Their results showed that high-calibre players exhibit an increased stride rate and a decreased amount of time spent in both single and double support compared with low-calibre players. High-calibre players also showed a deceleration of hip and knee extension as the centre of gravity was anterior to the support foot. No such measurable deceleration in the novice skater was observed (McCaw and Hoshizaki, 1987). Their work suggests that kinematics play an important role in describing the proficiency of the skating stride and that important differences become apparent as skill increases.

Past kinematics research of forward hockey skating has investigated individual joint angles during stride. Pearsall and colleagues (Pearsall, Chang, Turcotte, Lefebvre, and Montgomery, 2002) examined the angular motion of the ankle during the skating stride using bilateral twin axis electrogoniometers placed on the rear foot along the longitudinal axis of the Achilles tendon, thus allowing simultaneous measurement of angles in two planes. However, there are unanswered questions about whole-body kinematics during forward skating. Unlike dry land walking or running, skating locomotion involves substantial movements in both sagittal and frontal planes. Despite the obvious medial–lateral sinusoidal body migration during skating, limited quantitative measures in this plane have been obtained. For example, it is unknown to what extent the amount and rate of hip internal and external rotation, as well as hip abduction and adduction, occur during blade contact and push-off. In an attempt to record whole-body kinematics during forward skating, McPherson and colleagues (McPherson, Wrigley, and Montelpare, 2004) studied developmental age hockey players. Using kinematic data, including joint angles of the hip, knee, and ankle at various points during the stride, they developed regression functions to predict skating speed. The predictive equations related to horizontal impulse included six parameters: knee angle at push-off and touchdown, take-off angle (blade-to-ice) at push-off, hip abduction angle at push-off, range of motion of forward lean angle, and player mass. Although systematic kinematics patterns were not reported, their findings indicate that skating calibre corresponds to several kinematic variables both within the sagittal and frontal planes.

To quantify precisely forward hockey skating kinematics, data must be collected in a controlled environment that simulates on-ice skating conditions. Using a skating treadmill provides such an environment. The skating treadmill is thought to be representative of skating on an ice surface. Phasic muscle activity of the tibialis anterior, vastus medialis, rectus femoris, gastrocnemius, biceps femoris, and gluteus maximus showed no significant differences when measured during a skating task on the skating treadmill and on-ice conditions (Hinrichs, 1994). These findings would suggest that there may also be no significant differences in kinematics between conditions. The aim of the present study was to compare the three-dimensional kinematics of the lower limbs of high-calibre and low-calibre ice hockey players during forward hockey skating to provide a more complete description of the ice-hockey skating stride, including lower limb segment orientation as well as joint angles. Specifically, the three-dimensional angular kinematics of the hip, knee, and ankle during blade contact and push-off of the right limb were examined. We hypothesized that there would be significant kinematic differences between high-calibre and low-calibre hockey players, as has been suggested by related studies (de Boer, Schermrerhorn, Gademan, de Groot, and van Ingen Schenau, 1986; McCaw and Hoshizaki, 1987). Such differences may well be apparent through joint angles or segment orientation with respect to adjoining segments or a global coordinate system. The present study should help researchers, coaches, and hockey players achieve a better understanding of the mechanics of the forward skating stride. Players will then be able to apply this knowledge to their own skating stride, thereby transitioning quickly from an intermediate standard of play to a high-calibre standard of play.

Methods

Operational definition of terms

- *Forward hockey skating*: forward hockey skating is characterized by its specific application to the sport of ice hockey.
- *Global coordinate system*: fixed coordinate system in the laboratory from which all positions are derived (Robertson, Caldwell, Hamill, Kamen, and Whittlesey, 2004). The GCS is an orthogonal system.
- *Kinematics*: kinematics allows determination of position, velocity, and acceleration by examining an object's speed and spatial position (Hamill and Knutzen, 1995).
- *Local coordinate system*: reference system that is fixed within a body or a segment and moves with the body or segment (Robertson et al., 2004). The LCS is an orthogonal system.
- *Stride*: biphasic motion of skating, which begins when the foot contacts the ice with the heel of the blade and progresses through glide, push-off, and recovery of the ipsilateral limb (Pearsall et al., 2000).
- *Weight acceptance*: the time event when full blade contact with the skating surface occurs, permitting support of the body's weight (Adams and Perry, 2006).

Participants

Ten hockey players from the general public and the McGill University men's varsity ice hockey team (age 37 ± 18 years, height 1.82 ± 0.01 m, body mass 89.4 ± 18.0 kg) volunteered to participate in this study. Participants were classified as either high calibre or low calibre based on their league of play and years of experience. There were five participants in each of the high-calibre and low-calibre categories. High-calibre and low-calibre participants were similar in age, height, and mass and all participants were right leg dominant (Table I). All participants were informed of the experimental procedures and subsequently signed an informed consent form approved by the McGill University Board of Ethics stating their understanding of the risks and benefits associated with the study.

Instrumentation and experimental set-up

All data were collected in a controlled indoor laboratory environment in the Seagram Sport Science Centre at McGill University. A skating treadmill (Frappier Acceleration Sport Training) was set at an inclination of 2° to simulate on-ice skating conditions. Four 1.33-megapixel digital video camcorders (Cannon Optra 200 MC) were used to film the participants at 60 frames per second (deBoer et al., 1986). Cameras were placed in the four corners of the laboratory at a diagonal distance of between 1.5 and 3 m from the centre of the treadmill (Figure 1). A calibration grid was created by hanging 21 spherical reflective markers (25 mm diameter) from the ceiling in a random pattern throughout the skating space above the treadmill. Four high-intensity lights were placed alongside the four cameras and were used to help illuminate the reflective markers. The calibration grid was filmed for 5 s before and subsequent to data collection for each participant.

Experimental procedure

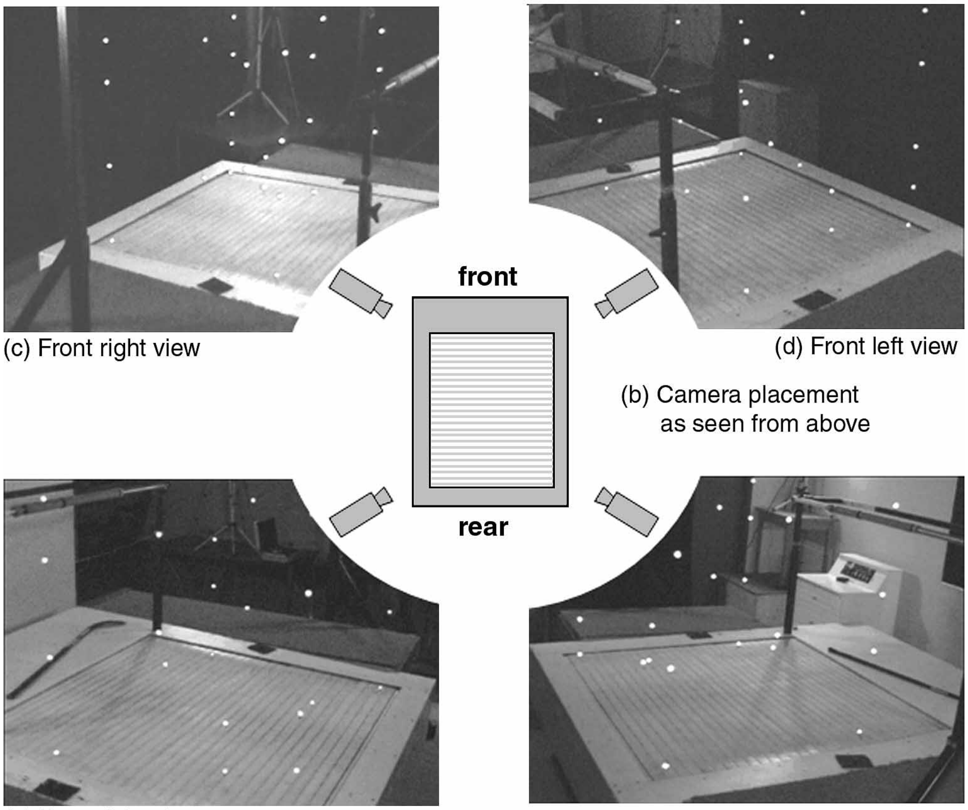
Participants underwent an accommodation period of approximately 2 h, during which they were introduced to the skating treadmill, given an explanation of its operation and safety features, and practised skating on the treadmill. During the accommodation period, participants were instructed to choose the maximum speed that they could comfortably maintain for a period of 1 min as a prelude to the conditions during data collection. A 1-min period was chosen so that there would be sufficient time for the capture of a minimum of 15 full, consecutive strides. Participants performed one-legged hop tests with both their right

Table I. Characteristics of low-calibre and high-calibre participants (mean ± standard error).

	Low-calibre	High-calibre
Age	31 ± 4.2	25.5 ± 2.0
Height (m)	1.81 ± 0.03	1.79 ± 0.01
Weight (kg)	86.2 ± 4.0	87.5 ± 2.4
Treadmill grade (%)	2.0 ± 0.0	2.0 ± 0.0
Treadmill speed (km/h)	13.6 ± 0.7	17.6 ± 0.3*
Stride rate (strides/min)	55.1 ± 1.2	59.9 ± 1.5
Vertical jump (%height)	21 ± 4	29 ± 1
Left leg long jump (%height)	95 ± 4	116 ± 3*
Right leg long jump (%height)	85 ± 12	115 ± 2*

*Significantly different from the low-calibre group: $P < 0.05$.

(a) Skating treadmill



(c) Front right view

(d) Front left view

(b) Camera placement
as seen from above

(e) Rear right view

(f) Rear left view

Figure 1. Experimental set-up in Seagram Sports Science Centre, McGill University.

and left legs, as well as vertical jump tests as a measure of leg strength (Kea, Kramer, Forwell, and Birmingham, 2001). Each test was repeated three times.

Rigid clusters consisting of three spherical reflective markers (5 mm diameter) in a triangular formation (Figure 2a) were attached with double-sided Velcro to the right and left thigh, shank, and foot. A single cluster was attached to the pelvis on the sacrum.

Before the skating task, an anatomical reference position was determined for each participant. Participants were filmed standing stationary on the treadmill within the calibrated space for a period of 5 s. Participants wore a safety harness attached to the overhead crossbar of the treadmill and held a hockey stick in one hand as they would while skating on ice during a hockey game. They held on to the treadmill safety bar in front of them with the other hand as the treadmill reached the predetermined participant-selected speed. Once the treadmill had reached its predetermined speed, participants let go of the crossbar and began skating. Cameras began filming and were synchronized with a light-emitting diode (LED), which was triggered at the beginning of each trial. Participants performed three trials of 1 min duration with 5 min of rest between trials.

Data analysis

Video capture and three-dimensional image reconstruction. Four digital video cameras recorded a given stride cycle (defined from initial blade contact to subsequent blade contact of right skate). After data capture, all video files were de-laced using a laboratory-specific program written in Matlab, to double the sampling rate from 30 to 60 frames per second (deBoer et al., 1986). The reconstruction from four two-dimensional images to a three-dimensional space was accomplished using the Direct Linear Transformation method (Nigg and Herzog, 1999). All digitizing was done using a laboratory-specific program (Loop) written in Matlab.

Joint angle calculations. The joint coordinate system (JCS) method for calculating joint angles requires the orientation of mechanical axes (Figure 2a) for segments about a given joint (Grood and Suntay, 1983). These axes consist of three orthogonal unit vectors that point anterior, lateral, and proximal relative to the segment. The orientation was calculated from a

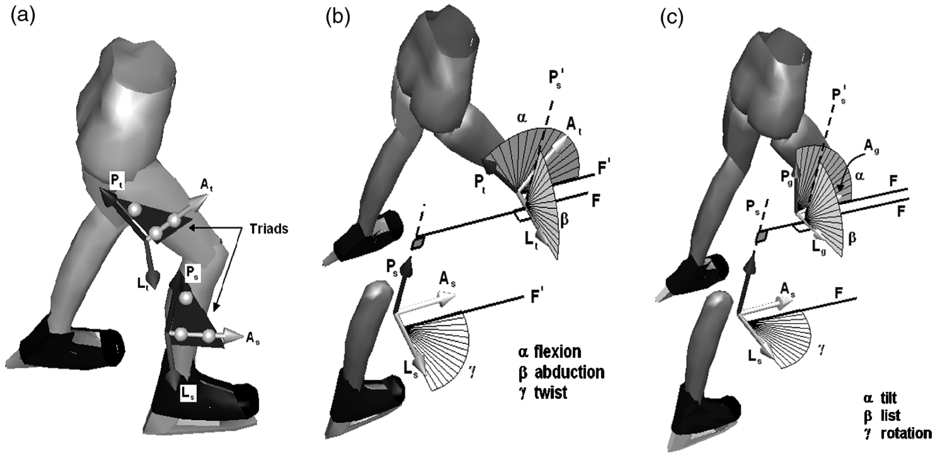


Figure 2. (a) The triads and the respective mechanical axes for the thigh (t) and the shank (s). Each mechanical axis consists of an Anterior (A), Lateral (L), and a Proximal (P) vector. (b) The method for determining the flexion, abduction, and twist about the knee requires the mechanical axes for the thigh (t) and the shank (s). The floating vector (**F**) was the cross-product between $\mathbf{P}_s$ (the proximal unit vector of the shank) and $\mathbf{L}_t$ (the lateral unit vector of the thigh). $\mathbf{F}'$ is a vector of the same orientation as vector **F**, but the displacement is different and likewise for vector $\mathbf{P}_s'$. (c) The method for determining the tilt, list, and rotation angles of the right shank is similar to that in (b) except the mechanical axes of the thigh are replaced with the mechanical axes of the global (g) coordinate system.

given triad placed on the pelvis, thigh, shank, and foot (Figure 2a). Figure 2b shows the JCS method to determine the flexion, abduction, and axial rotation about the knee.

Tilt, list, and rotation angles describe the global orientation of a segment (Figure 2c), giving a more complete description of the hockey skating task. These terms were adapted from literature in kinesiology to distinguish them from the commonly known pitch, yaw, and roll Euler angles (see Appendix).

Statistics. Joint and segment angles were calculated within stride cycles (initial blade contact to subsequent blade contact of right skate) using a laboratory-specific statistical analysis program written in Matlab. Alpha levels were set at 0.05 for significance. At the specific events defined as "weight acceptance" and "propulsion" (Figure 3), these dependent variables were analysed using a one-way analysis of variance (high calibre vs. low calibre). Tukey *post hoc* analysis was performed to determine pair-wise significant differences.

Results

High-calibre participants achieved faster skating velocities than low-calibre participants even though their stride rates were similar. High-calibre participants demonstrated both significantly greater stride length and stride width than low-calibre participants (Table II, Figure 4). Furthermore, high-calibre participants demonstrated greater leg strength as determined from distance measures from long ($P < 0.05$) and vertical jump tests ($P < 0.05$; 0.075).

Notwithstanding variation in skating techniques among individuals, several significant differences for both joint and segment angles within the skating gait cycle were observed between high-calibre and low-calibre groups (Tables III and IV, Figures 5 and 6). In general, the largest ranges of motions were observed in the sagittal plane. High-calibre athletes demonstrated greater hip flexion at weight acceptance ($P < 0.001$), greater knee extension and plantar flexion at propulsion ($P < 0.001$; $P < 0.02$), and greater knee and ankle–foot

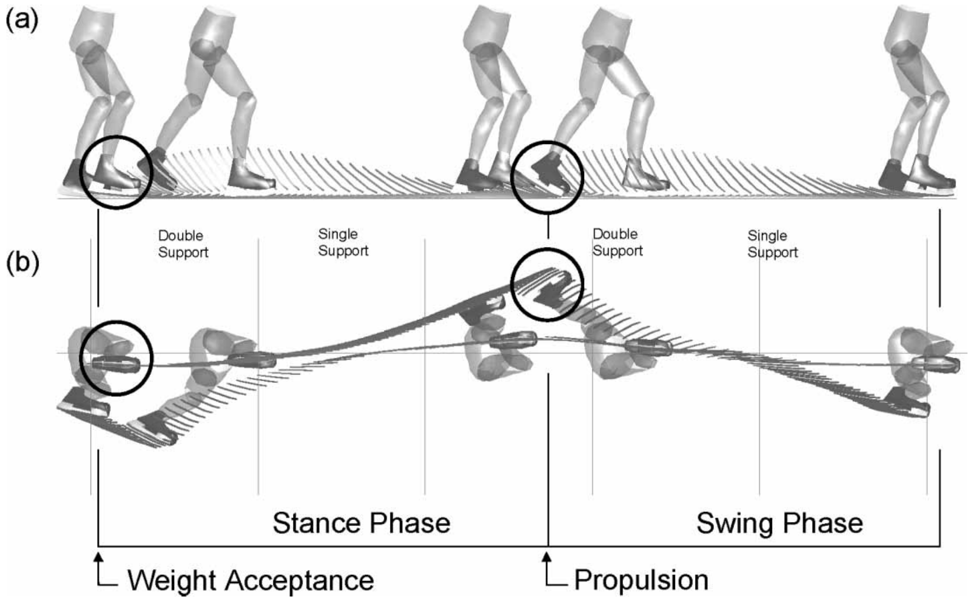


Figure 3. Phases and events of skating stride: side (a) and inferior (b) views.

Table II. Stride length and width (means and standard deviations, *s*).

	High-calibre		Low-calibre		
	mean	*s*	mean	*s*	*P*
Stride width (cm)	63.8	8.6	52.5	7.6	0.0483
Stride length (cm)	520.5	0.5	442.1	0.4	0.0000

ranges of motion ($P < 0.01$; $P < 0.02$). Closer inspection of the kinematic profiles suggested that technique differences exist between the skating groups. For instance, high-calibre skaters were more flexed at the hip and knee, and more dorsiflexed at the foot–ankle throughout support. In particular, high-calibre skaters maintained deeper knee flexion until much later in the stance phase, cumulating in rapid extension during propulsion. Corresponding limb segment orientation angle differences were seen between groups. Large differences were observed, with high-calibre skaters showing greater shank and foot anterior tilt inclination ($P < 0.04$; $P < 0.05$) during weight acceptance and greater rates of posterior tilt of the pelvis, thigh, shank, and foot during propulsion ($P < 0.05$; $P < 0.01$; $P < 0.01$; $P < 0.05$). Similarly, high-calibre skaters presented greater limb excursion (lateral displacement of lower limb segments) range of motion for the pelvis, thigh, and foot ($P < 0.03$; $P < 0.01$; $P < 0.07$).

In the frontal plane, comparable joint kinematic profiles were observed across skater ability. In general, hip abduction peaked twice during the skating cycle: initially at 8% during weight acceptance and at 60% near the end of the propulsion phase. High-calibre skaters showed a greater rate of abduction during weight acceptance ($P = 0.09$) and a greater range of motion through stance (13° vs, 9°; $P = 0.18$) than the low-calibre cohort. Knee abduction (valgus) movements were small for both groups, varying from 8° at weight acceptance to 0° at propulsion. For the foot (skate), weight acceptance began with the foot slightly everted (5–7°), increasing towards and peaking at 18° eversion at the mid-propulsion phase. In contrast, limb segments were oriented with a greater inward inclination (list) and range of motion for high-calibre skaters. For instance, the thigh, shank, and foot were found to be significantly more inclined at the end of the propulsion phase ($P < 0.01$; $P < 0.02$; $P < 0.09$) for high-calibre skaters. A greater range of motion in the excursions of the pelvis and limbs was also observed for high-calibre skaters ($P < 0.01$ to 0.08).

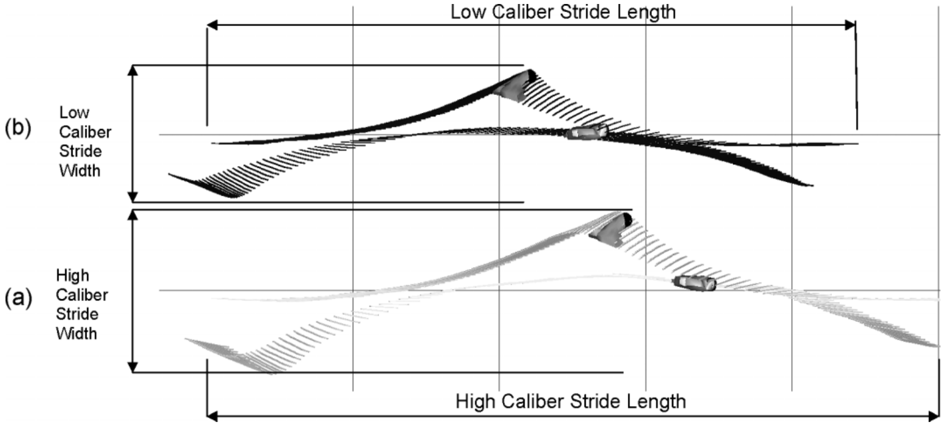


Figure 4. Comparison of stride width and length for (a) the high-calibre and (b) the low-calibre cohort.

Table III. Mean kinematic angles for high-calibre and low-calibre players at weight acceptance and propulsion (means and standard errors, $s_{\bar{x}}$).

		Weight acceptance					Propulsion				
		High-calibre		Low-calibre			High-calibre		Low-calibre		
Angle (°)		mean	$s_{\bar{x}}$	mean	$s_{\bar{x}}$	P	mean	$s_{\bar{x}}$	mean	$s_{\bar{x}}$	P
Flexion	Foot	−3.0	1.5	−1.2	1.9		11.1	1.9	12.3	1.4	
	Knee	**48.2**	1.7	**29.1**	1.9	**	13.4	2.6	8.0	1.9	
	Hip	−42.8	1.5	−41.6	2.4		−2.5	2.4	−2.2	1.3	
Abduction	Foot	5.2	1.2	6.7	1.4		6.2	1.4	7.5	1.6	
	Knee	**−1.9**		**−9.2**	1.7	**	**4.7**	1.1	**−0.5**	0.9	**
	Hip	0.2	2.1	0.7	1.2		6.6	2.4	9.2	0.6	
Rotation	Foot	1.0	0.6	2.6	0.7		6.9	0.9	10.0	0.7	
	Knee	−0.4	1.4	−5.2	0.9		1.0	0.8	2.1	2.0	
	Hip	1.4	1.3	3.3	1.6		5.5	1.4	7.8	1.9	

Note: All values are presented in the local coordinate system. **$P < 0.05$

In the transverse (horizontal) plane, both groups showed similar joint movements. At initial weight acceptance, the hip was in the neutral position moving towards full external rotation at the end of propulsion (5–8°). Knee rotations were minimal, although the high-calibre skaters tended to be moderately externally rotated (1–6°) as opposed to internally rotated (3–6°) for the low-calibre skaters during stance. Although these angular differences were small, they were calculated to be significantly different ($P < 0.03$). For the foot internal–external rotation (or abduction–adduction), the skater's foot position ranged from neutral to 10° during the end of stance (propulsion phase). For segment orientations, range of motion tended to increase from the most proximal segment (pelvis ± 10°), to the thigh (± 15°), shank (± 25°), and ending at the most distal segment (foot ± 30°). Both groups displayed similar trends, although the high-calibre skaters had significantly greater pelvic rotation range of motion ($P < 0.01$) and greater rates of rotation during weight acceptance and propulsion phases ($P = 0.14$; $P = 0.07$).

Discussion and implications

The objectives of the study were to describe lower limb kinematics in three dimensions during the forward skating stride in hockey players using a skating treadmill, as well as to contrast skating techniques between low-calibre and high-calibre athletes.

Results of this study indicate that there are significant kinematic differences between skill levels at both the weight acceptance phase of the stride and the propulsion phase of the stride. High-calibre athletes showed significantly greater knee abduction at both propulsion and weight acceptance than low-calibre athletes. The lesser knee abduction in low-calibre athletes could be a result of increased co-contraction of the sartorius and vastus medialis muscles to increase stability of the knee during the stance phase (Zhang and Wang, 2001), but may also be the result of a less skilled athlete being more cautious while skating on the treadmill. Knee flexion was also significantly greater at weight acceptance in high-calibre athletes than low-calibre athletes. An increased knee flexion at weight acceptance suggests the ability to transfer more elastic energy to the quadriceps for concentric contraction during the propulsive phase, which translates to a greater power generation during the end of propulsion (Marino, Hermiston, and Hoshizaki, 1989). This is consistent both with the

Table IV. Mean angular velocities (degrees/second) for high calibre and low calibre players at propulsion and weight acceptance. All values are presented in the local coordinate system.

		Weight Acceptance					Propulsion				
		High Calibre		Low Calibre			High Calibre		Low Calibre		
RATE (degrees/second)		mean	std	mean	std	p	mean	std	mean	std	p
Flexion	Foot	41.2	41.0	20.5	32.8	0.366	**214.4**	53.3	**110.0**	67.2	**0.016**
	Knee	−79.3	56.4	−1.5	81.7	0.086	**−212.1**	36.4	**−115.1**	38.2	**0.001**
	Hip	**51.6**	21.9	**4.6**	27.9	**0.009**	−177.9	32.8	−161.1	44.4	0.541
Abduction	Foot	40.5	28.5	36.7	20.8	0.830	−73.4	28.4	−64.2	34.6	0.663
	Knee	−8.5	17.9	1.4	27.4	0.478	3.7	16.5	8.5	26.1	0.710
	Hip	75.8	11.2	48.5	32.0	0.088	63.6	45.2	39.6	19.0	0.270
Rotation	Foot	13.4	41.1	49.4	23.6	0.088	18.0	28.7	6.4	25.7	0.483
	Knee	12.4	52.3	−26.5	43.7	0.191	15.4	38.2	43.4	74.5	0.427
	Hip	−2.1	28.7	22.5	39.5	0.244	4.8	33.3	6.2	26.3	0.930

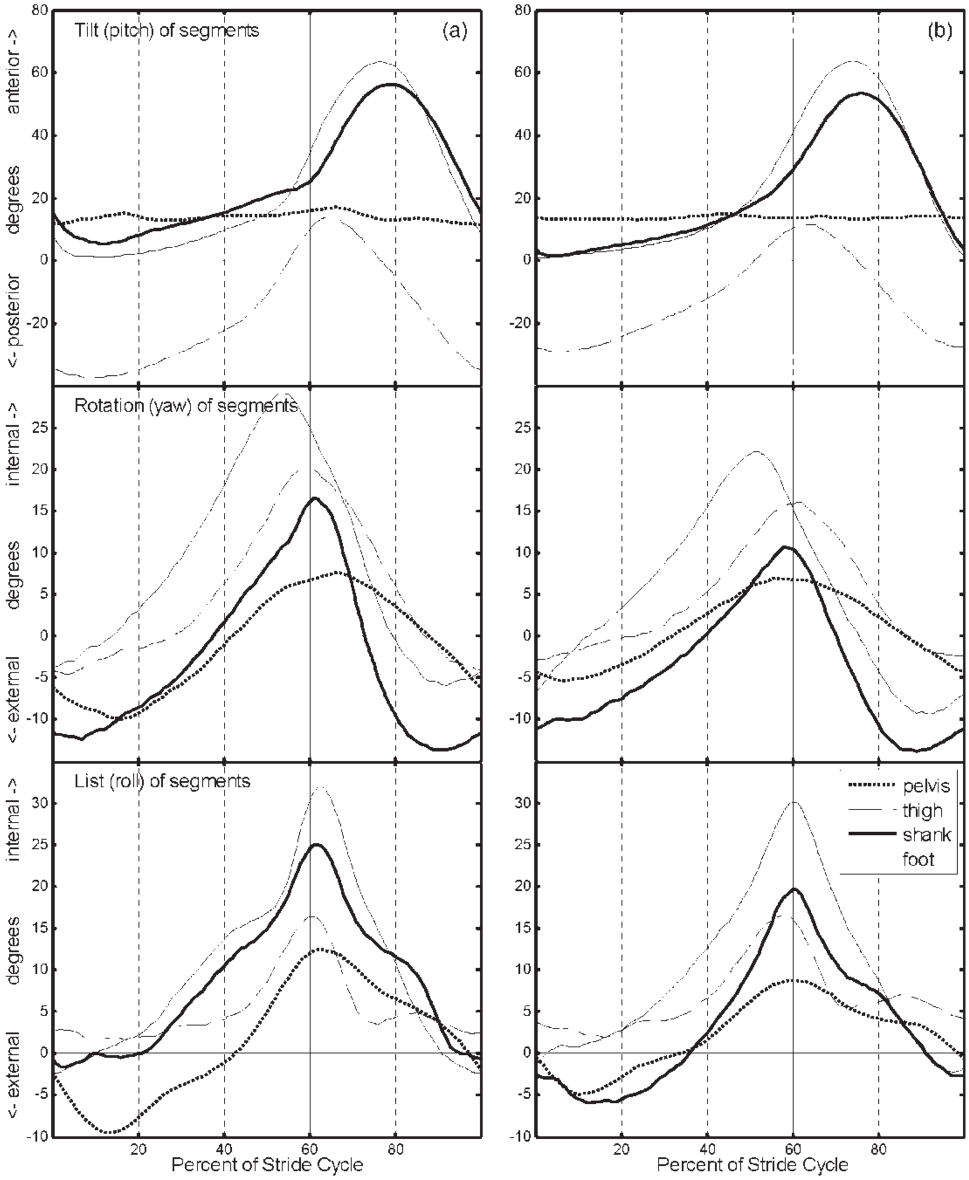


Figure 5. Global segment angles for (a) the high-calibre and (b) the low-calibre cohort.

greater vertical jump height and long jump distances exhibited by the high-calibre cohort (Table I) and trends in the literature (McCaw and Hoshizaki, 1987).

The greater rate of hip flexion at weight acceptance exhibited by the high-calibre cohort (Table III) is supported by McCaw and Hoshizaki (1987), who report greater hip angular velocity in high-calibre skaters than in novice and intermediate skaters over the course of the hockey skating stride. A greater rate of hip flexion at weight acceptance is indicative of a greater degree of eccentric contraction of the anterior muscles of the thigh before concentric contraction during propulsion. This transfer of elastic energy may possibly create a more powerful force at propulsion, leading to increased skating velocities. Similarly, the greater

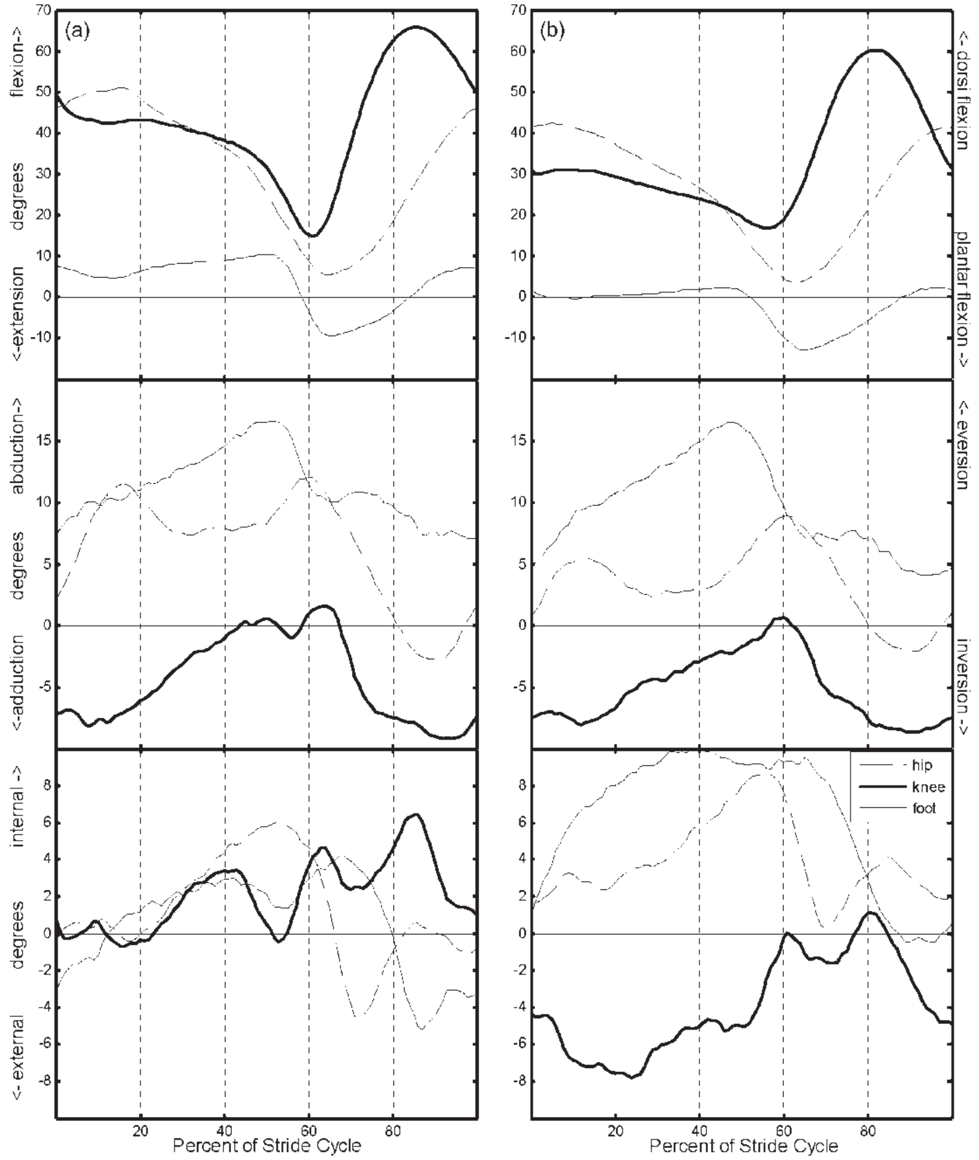


Figure 6. Local joint angles for (a) the high-calibre and (b) the low-calibre cohort.

rate of knee extension and plantar flexion at propulsion in the high-calibre cohort (Table III) is likely due to more power being generated by the high-calibre skaters, and likely contributes to increased skating speed. These findings are also supported by a previous study reporting greater angular velocity of the knee over the course of a skating stride in high-calibre hockey skaters (McCaw and Hoshizaki, 1987). Similarities, however, should be interpreted with care due to methodological differences, primarily differences in three-dimensional versus two-dimensional data collection.

The greater range of motion observed in the high-calibre skaters for most segments and joint angles throughout the stance phase are consistent with the longer stride length observed in high-calibre compared with low-calibre hockey skaters (McCaw and Hohshizaki 1987).

Greater ranges of motion in the hip and the knee have been reported to result in greater extension velocities during the stance phase of the skating cycle, and therefore greater force application at propulsion (de Koning, Thomas, Berger, de Groot, and van Ingen Schenau, 1995). This greater range of motion is evident in most of three planes of motion and is likely responsible for increased skating speed in the high-calibre athletes studied here. De Koning et al. (1995) suggest that increased skating speed should result in an increased amount of hip abduction to maintain a sufficient propulsive angle. Although De Koning et al. (1995) presented results for speed skating rather than hockey skating, both speed skating and forward hockey skating demonstrate similar muscle activation patterns in the legs, suggesting that kinematic patterns of the legs may also be similar. Results of the present study showed no significant differences between skill levels, despite the greater skating speeds maintained by the high-calibre athletes. Notwithstanding the limited frontal plane differences in joint movement patterns, high-calibre athletes demonstrated significantly more tilting of the lower limb, which is in line with both the greater stride width observed and a more oblique skate-to-ice interface, which in turn may provide a better edge for push-off.

Figure 5 demonstrates that the ankle is in a constant state of eversion throughout the stride, peaking at just over 15° during the propulsive phase of the stride, then decreasing to just over 10° during the later stages of the recovery phase. Pearsall et al. (2002) report similar kinematic patterns, although their findings suggest that the ankle is clearly inverted beyond 60% stride (3.5° inversion). Differences in findings may be due to varying methods. Pearsall et al. (2002) used twin axis electrogoniometers placed on the rear foot along the longitudinal axis to measure ankle kinematics, while the present study used reflective triads placed on the exterior of the skate boot, and estimated where the medial and lateral malleoli lie. Hence, the current study will have underestimated inversion owing to the rigidity of the skate boot, masking anatomical movements. Potential error exists in our measurement technique, as it has been shown that significant differences in bone, skin, and skate rotations exist in the ankle joint during the skating motion. Al-Hamill and Knutzen (1995)] reported significantly smaller skate rotations than bone rotations from dorsiflexion to plantar flexion throughout the skating stride. Skate rotations were 26% smaller than bone rotations and 49% smaller than skin rotations, while bone rotations were 31% smaller than skin rotations, thus suggesting that the rigidity of the skate boot causes an underestimation of the motions of bone and skin in the ankle joint (Al Hadi, 2002).

It should also be noted that each participant wore the skates that he uses to skate in regularly. Although differences in skate make and model may very well introduce variability into ankle and knee kinematics, we felt that within the time frame allotted for the project, providing participants with new skates, not yet conformed to the participants' specific foot anthropometry, would introduce greater variability into our results. Whole-body kinematics in developmental-aged hockey players was recently recorded during an on-ice acceleration skill test (McPherson et al., 2004). Mean hip, knee, and ankle angles were reported at push-off (149°, 156°, and 99°, respectively) and mean hip and knee angles were reported at touchdown (91° and 103°, respectively). Reported angles in the above study are defined as the angle between adjoining segments, and are markedly different from the values reported in the present study at corresponding points in the stride (propulsion and weight acceptance). While the above study was one of the first of its kind to measure three-dimensional skating kinematics on-ice, results may not be representative of the characteristics of a fully developed hockey skater. Discrepancies may be largely due to differences in the study population, means of measurement, and measured task. McPherson et al. (2004) were interested in studying developmental aged hockey players (mean age 10 years), whose anthropometric measurements, years of skating experience, and standard of play were clearly different from those of the present study. The joint angular kinematics reported was defined using a point spatial model as opposed to tracking three-dimensional segmental positions using a series of rigid clusters to define joint angles, as is now common practice (Capozzo, Catani, Della Croce, and Leardini, 1995; Winter, 2005). Furthermore, hip angle was defined as the angle of the thigh with respect to the trunk, without consideration of the segmental orientation of the pelvis. This could explain the large discrepancies in hip angle at both weight acceptance and propulsion between the present study and previous studies (Marino, 1983; Marino and Weese, 1979; McPherson et al., 2004).

Although skating speed differed between low-calibre and high-calibre athletes, stride rate was not significantly different between the two groups (high-calibre: 59.9 ± 7.6 strides/min; low-calibre: 55.1 ± 3.4 strides/min). The greater speeds observed for high-calibre skaters could be attributed to kinematic differences in the recovery phase of the stride. The increased stride width of high-calibre skaters may also contribute to greater forward speed by enabling a more oblique skate orientation to the skating surface, with the more stable blade edge permitting an effective push-off.

The results of this study show that high-calibre players exhibit a greater range and rate of joint motion in both sagittal and frontal planes than low-calibre athletes, contributing to greater stride length. Furthermore, consequent postural differences lead to greater lateral excursion during the power stroke in high-calibre skaters. These findings suggest that low-calibre hockey skaters will see improvement in forward hockey skating by lengthening their stride during the power phase of the stride, and striving for a greater range of motion throughout the skating stride.

This study has reported forward hockey skating kinematics of the lower limbs in three dimensions, as well as the kinematic differences between skill levels. Although movements in the sagittal plane, such as flexion and extension of the hip and knee, are among the largest contributors to forward propulsion, even small differences in joint rotations between skill levels may contribute significantly to stride efficiency. By addressing the differences in these lesser studied kinematic patterns, coaches will be able to help their players to transition quickly from an intermediate standard of play to high-calibre play.

Conclusion

While some aspects of the skating stride are similar in high- and low-calibre hockey skaters, there are several kinematic differences between them. High-calibre and low-calibre participants show significant differences during knee abduction, knee flexion, and knee internal–external rotation. By striving to adopt the skating kinematics of high-calibre hockey skaters, developmental age hockey skaters and low-calibre hockey skaters may develop a more efficient and effective stride thereby improving their overall performance during the hockey game. To understand more completely the kinematics of forward hockey skating, as well as to validate transferability of kinematic data collected using the skating treadmill to on-ice forward hockey skating, a whole-body, on-ice, three-dimensional analysis of the skating stride should be conducted.

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Appendix: Kinematic parameters

Angles	Segment	Plane
Global (segment)	Foot anterior (+) / posterior (−) tilt	sagittal plane (pitch)
	Tibia anterior (+) / posterior (−) tilt	sagittal plane
	Femur anterior (+) / posterior (−) tilt	sagittal plane
	Pelvis anterior (+) / posterior (−) tilt	sagittal plane
	Foot internal (+) / external (−) list	frontal plane (roll)
	Tibia internal (+) / external (−) list	frontal plane
	Femur internal (+) / external (−) list	frontal plane
	Pelvis internal (+) / external (−) list	frontal plane
	Foot internal (−) / external (+) rotation	transverse plane (yaw)
	Tibia internal (−) / external (+) rotation	transverse plane
	Femur internal (−) / external (+) rotation	transverse plane
	Pelvis internal (−) / external (+) rotation	transverse plane

Angles	Joint	Plane
Local (joint)	Foot and ankle plantar (−) / dorsiflexion (+)	sagittal
	Knee flexion (+) / extension (−)	sagittal
	Hip flexion (−) / extension (+)	sagittal
	Foot and ankle inversion (−) / eversion (+)	frontal
	Knee valgus (+) / varus (−) = abduction (+) / adduction (−)	frontal
	Hip abduction (+) / adduction (−)	frontal
	Foot and ankle abduction (+) / adduction (−)	transverse
	Knee internal (−) / external (+) rotation	transverse
	Hip internal (−) / external (+) rotation	transverse