Hockey Skating Kinematics and the Effect of Skate Design and Technique Training

Rebecca Mae Tidman
Marquette University

HOCKEY SKATING KINEMATICS AND THE EFFECT OF SKATE DESIGN AND TECHNIQUE TRAINING

by

Rebecca M. Tidman, B.S.

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ABSTRACT
HOCKEY SKATING KINEMATICS AND THE EFFECT OF SKATE DESIGN AND TECHNIQUE TRAINING

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The purpose of this study was to investigate the effects of technique training and hockey skate design on hockey skating performance. Fourteen male subjects, aged 12-16 years, with no recent skate treadmill experience completed ten training sessions on a skating treadmill. Instruction emphasized maximizing stride width by pushing laterally with the skate pointed anteriorly.

Subjects were randomly placed into one of two experimental groups based on initial skate type: traditional or Easton Mako. After completion of five sessions, skate type was switched so that skate design effects could be assessed. In contrast to a traditional hockey skate design, the Easton Mako skate incorporates a flexible tendon guard allowing greater ankle extension as well as a heat-moldable skate boot for greater conformity to the underlying anatomy.

Kinematic data were acquired during submaximal constant speed trials and maximum speed tests, at the first (baseline, skate 1), fifth (post-training, skate 1), sixth (baseline, skate 2), and tenth (post-acclimation, skate 2) training sessions. Treadmill training effects were investigated by contrasting data from sessions 1 and 5, and session6 and 10. Design effects were investigated contrasting data from sessions 5 and 6, and sessions 5 and 10; significance was assessed using paired t-tests.

Significant initial training effects included increased stride width and decreased anterior-posterior foot separation at foot off, with the foot less rotated out of the anterior-posterior direction as intended by the specific training program. Other effects included decreased stride rate at a constant speed and increased maximum speed. Initial training effects held through the latter training sessions suggesting five sessions were sufficient to adapt to the treadmill training. Significant skate design effects included decreased sagittal ankle range of motion (ROM), decreased stride rate at constant speed, increased stride width and increased maximum speed with the Mako skate. The decreased sagittal plane ankle ROM, perhaps counterintuitive with the more flexible skate design, may be indicative of a more natural ankle movement. As for treadmill training, the increased maximum speed in concert with decreased stride rate suggest potentially more efficient stride with the Mako skate.

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CHAPTER 1: INTRODUCTION AND MOTIVATION

Ice hockey is a complex sport requiring not only puck-handling skills, but technical skating ability as well. Skilled skating, including both high speed and agility, can allow a player to outpace and outmaneuver an opponent, giving them better opportunity to maintain control of the puck and potentially placing them in an advantageous scoring position. Previous hockey-related research has included observation of player tasks during National Hockey League (NHL) gameplay [2, 3], comparison of treadmill versus on-ice skating surface effects [4-6], definition of overall kinematics of skating [7-9], and injury mechanisms and prevention [10].

Observational studies of NHL players have quantified the mean time and frequency of occurrences of various on-ice skills during game play [2]. Nearly 40% of ice hockey play is spent in a two-foot gliding position with frequent changes in direction and short bursts of speed. Less than 5% of time on-ice is spent in possession of the puck. One study observed that during an average 961 seconds (approximately 15 minutes) of ice time in an NHL hockey game, there was an average of 301 skating movements or approximately one transition every 3.2 seconds [3]. These movements included starts, stops, cross over turns, and forward to backwards turns. The ability to change direction and accelerate quickly are therefore key skills for competitive hockey play. Forward skating ability is also important; in fact, forward skating at various intensities remains the most frequently assessed skill in hockey gameplay [2, 3].

Limited research has been conducted to investigate the effects of specific skating technique instruction or equipment, specifically that of the hockey skate, on skating performance. Investigation of skating performance is hindered by measurement challenges of on-ice data acquisition. Ice hockey skating is a fast-paced dynamic activity with large sagittal and coronal plane motion [11], necessitating a large capture volume on a bright, reflective surface that makes on-ice motion analysis difficult. Skating treadmills provide a controlled research environment for forward skating assessment although agility cannot be assessed.

Like many sports, ice hockey training regimes and techniques have generally been developed based on experience, and observation and mimicking of elite players, not quantitative evidence. More formal quantitative assessment of the efficacy of specific technique training will provide evidence of its validity to the athletic community. In addition to technique and skill development, quality equipment has the ability to enhance skating performance. Quantification of equipment effects will assist manufacturers in designing equipment that enhances, rather than hinders, performance; such data can also assist coaches and athletes in equipment selection.

The purpose of this study was to quantify the effects of treadmill technique training and hockey skate design on skating performance, and to more fully characterize hockey skating kinematics and temporal characteristics. The research questions to be addressed were: 1) Can skate treadmill training improve skating performance in terms of speed and efficiency? and 2) Does skate boot design affect skating performance in terms of posture, speed and efficiency? The related research objectives to be addressed in this study were that: 1) technique training incorporating a lateral stroke increases skating speed and skate stroke efficiency and 2) a skate boot with increased anterior-posterior flexibility accommodates a more crouched, ergonomic posture that results in increased skating speed and efficiency.

CHAPTER 2: BACKGROUND AND LITERATURE REVIEW

This chapter provides pertinent background information for understanding this study's motivation, objectives, and results as well as those of similar studies. A review of relevant literature is also presented. Topics include the physics of ice skating, skating technique, including the differences between the typical hockey and speed-skating stride, and a brief history of hockey skate design as well as previous research on the impact of design on performance.

2.1 PHYSICS OF ICE SKATING

The ice skating stride, unlike that for running and walking, includes large coronal as well as sagittal plane motion due to the unique low-friction interaction between the skate blade and ice surface [12, 13]. Physics dictates that while skating, the push-off force must be applied perpendicular to the skate blade [14]. In hockey arenas, the low coefficient of friction of ice is further reduced due to a thin lubricating layer of water on the ice surface. Additionally, the ice surface undergoes plastic deformation upon contact with the skate blade. As such, the skate blade penetrates the ice surface, creating an edge along the blade upon which lateral force can be applied; forces directed along the longitudinal axis of the blade result in negligible motion [14, 15].

2.1.1 Surface Pre-melting of Ice

Skating and skiing originally developed as methods of transportation in snow and ice covered regions. These methods of transportation take advantage of the slickness of ice; ice, like other solids, becomes slippery when a thin lubricating liquid layer is present at the surface. It was not until the mid-19th century that a theory explaining water formation on ice surfaces, in particular as it applies to skating and skiing, was developed. The predominant theory, originally proposed by James Thomson and later expanded upon by James Joly, states that high pressures, such as those created along a thin metal skate blade, melt the ice upon contact [15-17]. However, pressure melting only accounts for water formation from skate blade pressure down to -3.5°C. The ice in hockey and figure skating arenas is typically maintained at -9.0°C and -5.5°C, respectively, and anecdotal evidence suggests formation of a lubricating layer of water at temperatures as low as -35°C.

To account for surface melting at temperatures less than -3.5°C, two additional theories have been proposed: frictional heating and intrinsic pre-melting of ice. In the late 20th century, evidence of frictional heating was demonstrated by temperature increases in skate and ski blades with increasing velocity. However, the liquid layer at the ice surface is observed without increased pressure or friction, confirming intrinsic pre-melting of ice, a concept that was not generally accepted until the mid-20th century. Thermodynamics dictates that, if a liquid layer exists between a solid and gaseous interface, the free energy of the boundary is reduced relative to that with no liquid layer present, up to a specific, sub-freezing temperature [16, 17]. Experimental observations have confirmed that water molecules in top layer of ice are less tightly bound than those within the solid; these surface molecules display large vibrational and rotational motion supporting the concept of liquid surface layer (Figure 1) [15]. Ultimately, the combination of frictional heating and intrinsic pre-melting of ice is responsible for the low coefficient of friction of ice and the decreasing coefficient of friction as skate speed increases [15-17].

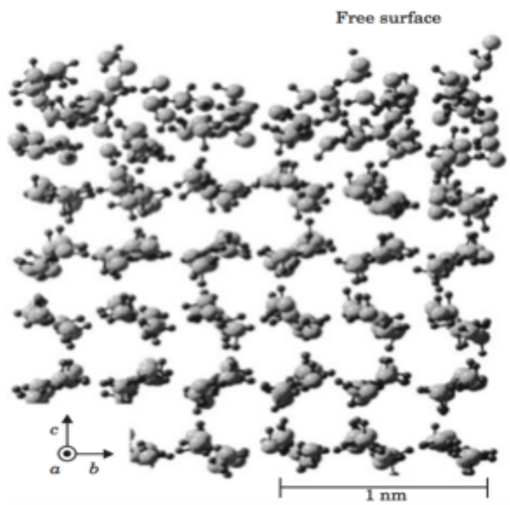

Figure 1. Ice surface structure at -20 deg C as demonstrated by a molecular-dynamics simulation. The large gray and small black spheres are oxygen and hydrogen respectively. Adapted from [14].

2.1.2 Skating on Synthetic Ice Surfaces

The development of synthetic ice surfaces has facilitated creation of skating arenas without the requisite cold environment and associated maintenance of the ice surface. The skating treadmill is also attributed to the development of synthetic ice; these treadmills in turn provide training and research benefits of a localized, speed-controlled environment. The speed of a skating treadmill can be adjusted, facilitating overspeed training that is difficult to implement during on-ice skating [18].

Synthetic ice is manufactured from either ultra-high or high molecular weight polyethylene. Most synthetic ice surfaces require a lubricant, often silicone or glycerin based, to simulate the low friction environment of ice. The high-density base coupled with the lubricant allows athletes to skate on the artificial surface as if it were ice. Skating treadmills are constructed from a series of polyethylene slats attached to a tread belt system and function similar to a running treadmill (Figure 2) [19]. Anecdotal comments from athletes suggest that synthetic ice initially feels sticky or slow, perhaps indicating a higher coefficient of friction than natural ice; however, no formal measurements of surface friction have been performed as yet to corroborate the anecdotal evidence. Several studies, however, have contrasted skating dynamics on synthetic vs. natural ice [4, 20, 21]. In general, these studies identified minimal differences in kinetics and kinematics during skating on the two surfaces; however, the increased friction on synthetic surfaces may affect skating economy. Nobes, Montgomery [20] compared skating economy on ice versus a skating treadmill in male varsity hockey players (N = 15, mean age = 21.0 yrs.) measuring oxygen expenditure, heart rate, stride rate, and stride length at three velocities (5.0, 5.6, and 6.1 m/s). Oxygen consumption, heart rate, and stride rate were elevated on the treadmill versus ice; these differences were greatest at slower velocities. Stidwill, Pearsall [5] also investigated ice versus synthetic surface effects on skating kinetics and sagittal plane kinematics (knee and ankle only) for adult male hockey players (N = 11, mean age = 21.5 yrs.). With the exception of knee extension, which was significantly greater on the synthetic surface, minimal kinematic or kinetic differences were observed between the two surfaces. Turcotte, Pearsall [4] observed increased heel loading (nearly 30%) at heel strike on the skating treadmill versus on ice for male university hockey players (N=4) at various speeds (6.1, 6.7, and 7.2 m/s).

Figure 2. Blade skating treadmill with overhead gantry system. Adapted from [19].

2.1.3 Force Production on Ice

The low coefficient of friction of ice is not conducive to forward motion. Traditional forms of terrestrial locomotion are inefficient and/or dangerous when performed on ice and snow. Force production in these forms of locomotion is dependent on the friction between the foot/wheel and the ground; forward propulsion is created by pushing backward against a fixed point on the ground. Maximum speed in running, for example, is limited by leg extension velocity as the point of force application remains fixed [13]. In ice skating, however, the skate blade continues to move forward with respect to the ground while pushing off due to the low friction between the blade and ice surface. While the mechanism remains poorly understood, friction heating and/or plastic deformation of the ice surface along the skate blade creates a trough, upon which force can be applied. As such, force must be applied along the lateral portion of the blade. To create forward motion, skaters rotate the blade out of direction of forward progression (Figure 3). Friction, opposing forward motion, increases as the blade is rotated; the magnitude of this rotation varies with skating technique and discipline [13, 14, 22].

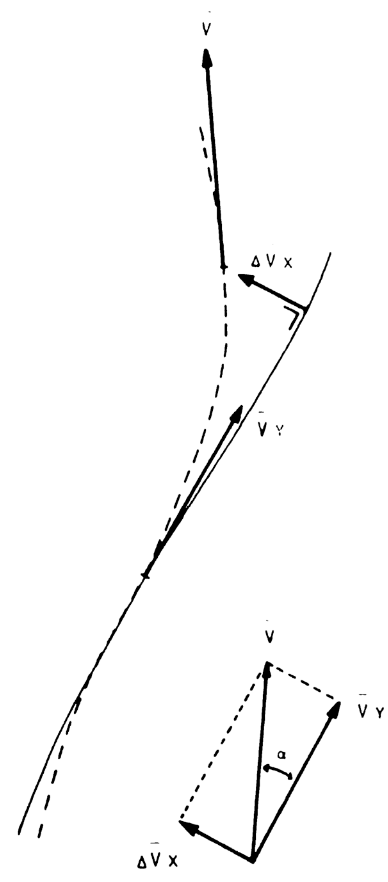

Figure 3. The push-off in ice skating. The trajectory of the center of gravity (CG, dashed line) and the right skate (solid line) are shown. The velocity vector, delta Vx, represents the velocity imparted to the system from the sidewards push-off. Vy is the initial velocity of the CG before push-off, and V is the resultant velocity of the CG just after push off. Adapted from [14]

2.2 HOCKEY SKATING TECHNIQUE

2.2.1 Skate Cycle Phases and Definitions

As for walking or running, skating can be divided into phases and periods of single and double limb support (Figure 4). Due to the paucity of ice skating research, there is as yet no consensus regarding how best to define the skate cycle. The skate stroke is typically divided into glide and recovery phases; a separate push-off phase may also be incorporated. The specific definition of these phases, however, varies [9, 11, 14]. For example, the initiation of the gliding phase may occur when the gliding skate is placed on the ice [9] or when the contralateral foot is lifted from the ice (when true weight acceptance occurs) [14]. Push off, when included, is defined as the period of increased knee extension and ankle plantar flexion motion, terminating when the foot is lifted from the ice. Recovery is generally defined as the period of non-contact with the ice, but may also include early double limb support prior to weight acceptance.

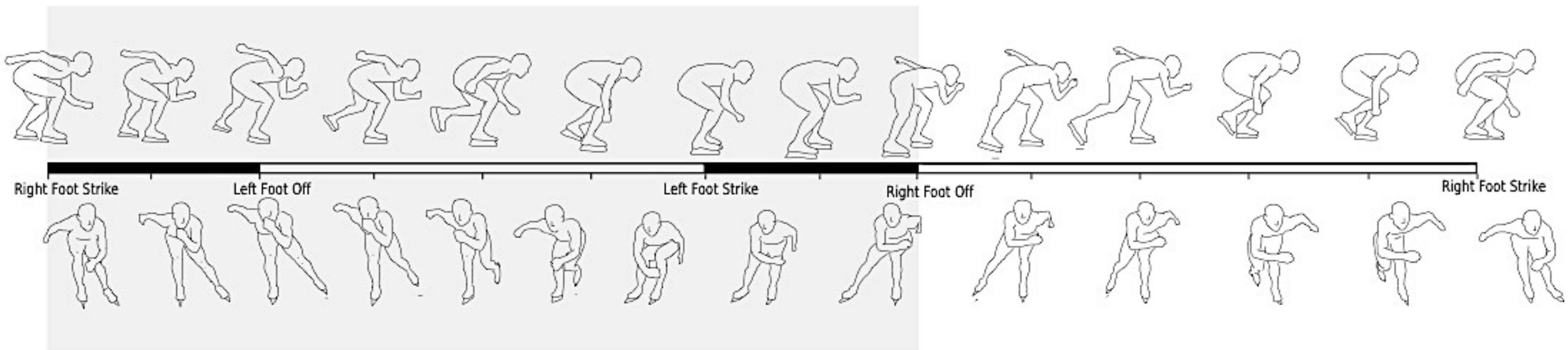

Figure 4. Skate stride cycle diagram. Periods of single and double limb support are indicated by the white and black bars, respectively. The glide period, in contrast to recovery period, is indicated by the shaded portion.

2.2.2 Speed Skating vs. Hockey Skating

Speed skaters utilize a stride that emphasizes lateral push-off while the skate remains more or less aligned in the forward gliding direction, thereby reducing frictional losses and maximizing contact duration to increase effective stroke work [13, 14] (Figure 5a). Stroke mechanics are less refined for hockey players. Hockey skating form typically involves external rotation of the push-off leg such that the skate blade is aligned at an angle of 45° or greater with respect to the direction of forward progression [23] (Figure 5b). This form and associated lower extremity kinematics contribute to posterior-laterally directed push-off force; the posterior force component is similar to that applied during running or walking [24]. In the extreme case, the external rotation and oblique skate blade orientation result in high friction and push-off against a point fixed on the ice, as opposed to a forward gliding contact point. This technique is effective for starts from rest (e.g., as in speed skating starts), but is less effective during peak skating velocity due to the requisite leg extension velocity and increased friction opposing forward progression [13, 14]. Despite evidence that a wider stride is correlated with increased speed [11, 23], this narrow, posterior push-off technique remains common for many hockey players. This inefficient form may be partly attributed to a skate boot that is stiffer for hockey than for speed skates, resulting in decreased ankle mobility [25, 26]. Regardless, training hockey players to employ a wider stride with increased lateral push-off has the potential to increase speed and stroke efficiency, thereby improving the skater's hockey performance.

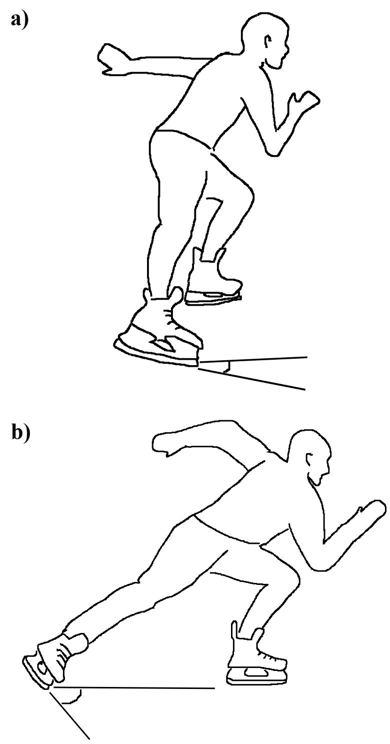

Figure 5. Skaters demonstrating alternative skating techniques characterized by a (a) wide, lateral push and (b) narrow, posterior push.

2.3 SKATE DESIGN

Ice hockey skate design has not changed significantly during the past 30-40 years since manufacturers replaced leather and metal designs with plastic and carbon composite skate boots and blade holders [25, 27]. These alternative materials provide increased protection and support, increasing boot stiffness and reducing mass [25, 26, 28]. However, the increased boot stiffness constrains ankle and subtalar joint motion and may adversely affect hockey player performance [25, 26]. The stiff skate boot may also limit plantar (push-off) force production, as has been observed in figure skaters [29]. However, reported effects of skate boot stiffness on hockey skating performance are inconclusive.

No significant differences in peak dorsiflexion or plantar flexion were observed for 10 subjects wearing two different hockey skates (traditional and an alternative design) with varying sagittal plane boot stiffness during passive ankle sagittal plane range of motion (ROM) tests [30].

Limited research has been conducted to quantify the effect of hockey skate boot design on skating performance. Robert-Lachaine et al. contrasted the effects of two different skate designs for 10 adult hockey players during three on-ice skating conditions: forward skating, and inside and outside leg cross-over turns [7]. Test skates included a standard skate as well as a modified Bauer One95 (Bauer Hockey, Exeter NH) skate that incorporated a lightweight, flexible tongue, raised eyelets and a tendon guard that was elastically, not rigidly, attached to the skate boot. Significantly increased peak plantar flexion, sagittal plane ankle ROM and plantar flexion angle at peak force were observed for the more flexible, alternative skate design. No significant differences with skate design were observed for other skating performance metrics (e.g. maximum dorsiflexion, task completion time, stride rate, vertical force, medial-lateral force, or total force, power or work).

Few studies have investigated the impact of *hockey* skate design on functional performance [7], although research has been conducted to investigate the effect of the clap skate on *speed* skating [31, 32]. The clap skate was developed after conducting biomechanical analyses of the speed skating stride. Speed skaters were observed to limit knee extension and ankle plantar flexion during push-off to prevent the skate blade from digging into the ice and increasing friction [31]. The clap skate incorporates a hinge between the boot and the blade holder, near the region of the metatarsal-phalangeal joint;

this design allows full plantar flexion without increasing friction at the blade-ice interface. The clap skate design was conceptualized in the 1980s and verified in 1996 [32]. This seminal research convinced elite speed skaters to adopt the clap skate and modify their skating technique, resulting in twelve new Olympic speed skating records (and five world records) for both men and women at the 1998 Nagano Olympics. Studies investigating hockey skate design have the potential for similar impact on hockey skating performance.

Prior investigations of hockey skating utilized various sensors and data collection techniques [6, 9, 12, 33]. Full description of three-dimensional kinematic and kinetic data during hockey skating is lacking. Kinematic studies of hockey and speed skating are typically limited to sagittal plane analysis via one or two camera motion analysis [6, 9, 12, 23, 33] or the use of two (not three) dimensional electrogoniometers on the lower extremity joints [5, 7]. The limited data may be partially attributed to the difficulty in performing on-ice motion analysis due to the requisite large capture volumes, cold environment, and highly reflective skating surface. Skating treadmills provide a contained observation and training environment in which technique can be assessed more easily. The purpose of this study is therefore not only to investigate the effects of skate design and skating technique on skating performance, but also to provide a more complete kinematic analysis of the hockey skating stride and to assist in defining metrics for assessing skating performance.

CHAPTER 3: METHODS

There is a lack of established hockey-related research due in part to the difficulty of obtaining on-ice performance measurements and the relative novelty of sports biomechanics research in general. The purpose of this study was to gather preliminary data to more fully characterize lower extremity kinematics during hockey skating and to quantify the effects of treadmill technique training and hockey skate design on skating performance. The specific research questions to be addressed were: 1) Can skate treadmill training improve skating performance in terms of speed and efficiency? and 2) Does skate boot design affect skating performance in terms of posture, speed and efficiency?

This chapter summarizes the methods used to address the research objectives of this study including subject selection, metrics of interest, specific research protocol, data processing, and statistical analyses.

3.1 SUBJECTS

3.1.1 Inclusion and Exclusion Criteria

The subject inclusion and exclusion criteria were selected to maximize effects of training and skate design while minimizing effects of gender and skating ability. The specific age range was selected so that subjects would be open to a new skating technique, but have sufficient hockey experience and skill to incorporate these changes effectively. The specific subject selection criteria were:

Inclusion Criteria:

- Male
- 12-16 years old
- At least 7 years previous hockey skating experience
- Physically able to participate in sport
- Able to skate unassisted for multiple 45 second periods on a skating treadmill

Subjects with more than 3 treadmill training sessions in the past 3 years were excluded from the study.

3.1.2 Subject Recruitment

Subjects were recruited by word of mouth by the treadmill skating trainer from those who were currently or had previously attended hockey camps at the Pettit National Ice Center (Milwaukee, WI) and by referrals from Marquette University professors. Subjects were informed in writing and briefed verbally of the study goals and participant requirements. Informed assent and parental consent were obtained from all subjects prior to study participation.

3.2 EXPERIMENTAL DESIGN AND TEST PROTOCOL

3.2.1 Study Design

In this crossover design, subjects were randomly assigned to one of two groups based on their initial test skate: non-Mako traditional skate (TRAD) or Mako skate (MAKO). Subjects wore their personal skates and received complimentary skates of an alternative design (e.g. Mako or non-Mako traditional skates); upon study completion, all subjects in the TRAD group were permitted to keep the Mako skates. Subjects with personal Mako skates were assigned to the MAKO group.

Test Protocol:

All subjects completed ten 45-minute treadmill training sessions over 2-3 months. Ten sessions and duration were scheduled to provide sufficient time to adjust to the new training technique and acclimate to the new skate type [6]. Subjects wore their personal skate (TRAD or MAKO) for the first 5 training sessions. After training session five, subjects switched to the alternative skate (TRAD group to Mako skate; MAKO group to non-Mako, traditional skate).

3.2.2 Treadmill Training

Treadmill training was conducted on a level skating treadmill consisting of polyethylene slats coated with a silicone lubricant (Woodway Blade, Waukesha, WI;

maximum speed of 8.94 m/s or 20 mi/hr, Figure 2). To minimize fall risk, subjects were secured in a safety harness tethered in an overhead gantry system; a stability bar at the front of the treadmill was also available, if necessary, for skater stabilization.

Each treadmill training session consisted of 10-15 minutes of warm-up at moderate, submaximal speeds, followed by 20-30 minutes of technique instruction by an experienced skater/trainer (L. Lambert, DC Hybrid Skating, Milwaukee, WI). The submaximal speeds were selected based on subject skill level and ability so as to minimize fatigue over the session duration. The technique instruction specifically addressed foot placement and stroke direction during push-off, as well as overall body position. Subjects were instructed to push in a predominantly lateral direction with their skates pointed forward (Figure 5a). Subjects were blinded to the treadmill speed. Subjects alternated periods of skating (15-60 sec) and rest (60-240 sec) to minimize fatigue risk.

3.2.3 Motion Capture

Motion capture was conducted at training sessions 1 (baseline: skate 1), 5 (post-training: skate 1), 6 (baseline, skate 2), and 10 (post-acclimation; skate 2) using a 6-camera motion capture system (Vicon Motion Systems, Ltd, Oxford, United Kingdom). During these test sessions, subjects wore a two-piece spandex suit to reduce clothing motion artifacts. Twenty retro-reflective markers (15 lower extremity, 5 torso) were positioned bilaterally based on the Helen Hayes system [34] (Figure 6). Specific marker locations for the lower extremity included the left and right second metatarsal, lateral malleolus, heel, shank, lateral femoral epicondyle, thigh, and anterior superior iliac spine;

a marker was also positioned over the midpoint between the posterior superior iliac spines. The second metatarsal, lateral malleolus and heel markers were placed superficially on the skate boot corresponding to the underlying anatomy. Torso markers were positioned over the T10 and C7 vertebra, the mid-right scapula, the suprasternal notch, and the xiphoid process.

An initial static calibration trial was conducted for each subject at each respective data collection session (1, 5, 6, and 10). After securing the 20 reflective markers, subjects stood in the center of the data collection volume with skates on while a 3-5 second static trial was captured. The static trial provided a means of confirming correct marker placement, defined potential calibration offset angles (not used in the current study), and created a skeleton template to facilitate automatic marker labeling during subsequent dynamic trials. Once an acceptable static calibration trial was obtained and the subject had completed sufficient warm-up, dynamic motion data (4-6 trials, 15-30s each) were acquired as the subject skated at submaximal constant speed. Trials were excluded if the fall arrest harness was engaged or if the subject reached out or grabbed the safety bar. All kinematic data were acquired at 100 Hz.

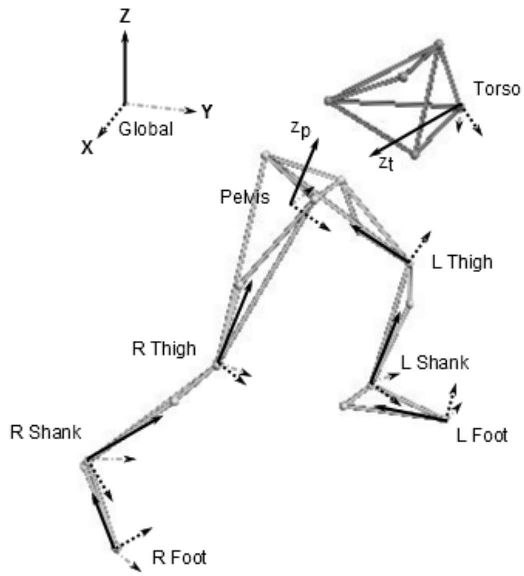

Figure 6. Global and local coordinate systems. Torso angle is defined relative to the global Z- and the local z- axes; spine angle is the relative angle between the local torso (z_t) and local pelvic (z-) axes in the sagittal plane.

Each motion analysis session also included two maximum speed tests that were conducted upon completion of the submaximal constant speed trials and a minimum 2-minute rest period. During these maximum speed tests, the trainer set the initial treadmill speed at a conservative estimate of the subject's maximum speed based on prior training session performance. The treadmill speed was gradually increased until the subject's skating form visibly deteriorated, the subject grabbed the safety bar, 20 sec had elapsed, or the safety harness was engaged. The rate of speed increase varied among subjects and was dependent on the accuracy of the trainer's initial estimate of peak speed; in general, treadmill speed increments were greater initially, with fine adjustment as the skater approached his maximum speed. The initial speed estimate for the second speed test trial was set to the maximum speed attained during the first trial, with minimal fine adjustment. This process was repeated at *each* motion analysis session to determine the maximum speed of the respective skate.

3.2.4 Metrics of Interest

Due to the scarcity of published hockey and speed skating research, and large variance of motion and/or kinematic data acquisition techniques reported in the literature, there are no clearly defined measures of skating performance. As such, this study also served as a means to help identify useful metrics of interest for future skating performance studies. To test the research hypotheses, the following kinematic and temporal metrics were evaluated:

Temporal and Stride Metrics:

- Maximum speed – greatest speed obtained during maximum speed trials.
- Stride rate – number of strides per second during constant speed trials.
- Stride width – maximum bilateral displacement of the lateral malleolus markers along the global x-direction (Figure 7).
- Percent time in glide vs. recovery periods – percent skate cycle with foot in partial or full contact (glide), or no contact (recovery) with the treadmill.
- Percent time in single vs. double limb support periods – percent skate cycle with one (single) or both (double) limbs in contact with the treadmill skating surface.

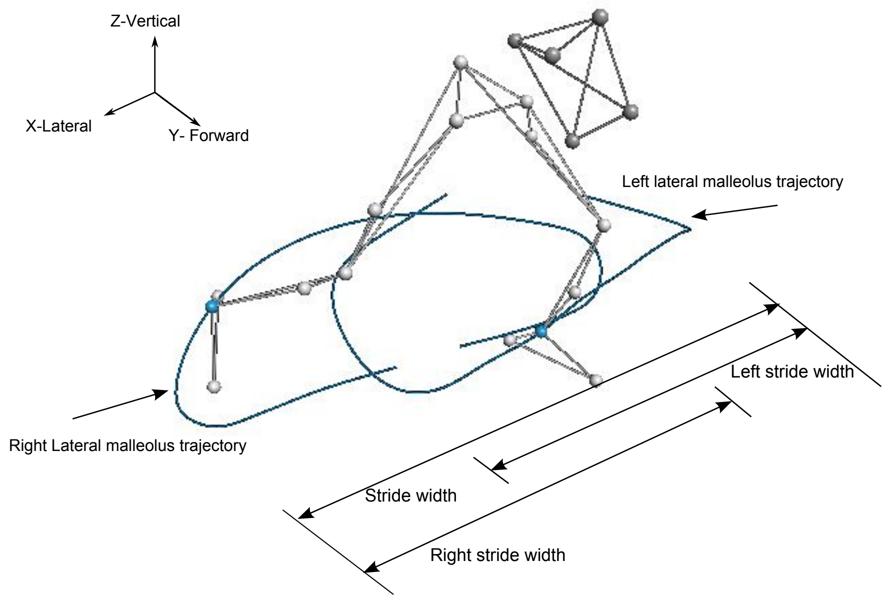

Figure 7. Trajectories of the lateral malleolus markers; also shown are the foot, shank, thigh, pelvic and torso segments. Stride width is defined as the maximum medial-lateral distance between the left and right foot/ankle.

Kinematic Metrics:

- Joint range of motion (ROM) – maximum angular displacement of the hip, knee, and ankle joints in all three planes of motion (sagittal, coronal, and transverse).
- Mean joint angle – mean relative joint angle of the hip, knee, and ankle joints in all three planes of motion for the entire skate cycle.
- Torso posture – mean torso position relative to both global (torso angle) and local (spine angle) reference frames for the entire skate cycle (Figure 6).
- Relative sacral height – vertical position of the sacral marker at foot strike, normalized with respect to sacral marker height during quiet standing with skates donned.
- Foot Placement – relative distance, at push-off, between the toe marker of the

stroke foot and the heel marker of the stance foot (Figure 8).

- Foot angle - angle of the stroke foot at push-off relative to the direction of forward progression (Figure 8).

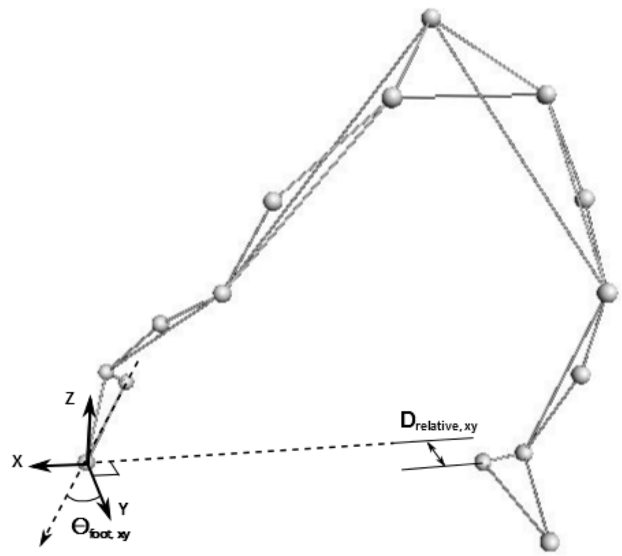

Figure 8. Foot (outset) angle, $\theta_{foot,xy}$, relative to forward progression, at foot-off in the transverse plane. $D_{relative,xy}$ is the relative anterior-posterior location of the push-off foot (right, as shown) relative to the stance foot (left, as shown).

These metrics of interest were selected as those most likely to be affected by the alternative technique training and/or Mako skate design. Specifically, the alternative technique training was expected to alter foot position and angle at foot off and stride width; these characteristics were the focus in the alternative technique. The more flexible tendon guard of the Mako skate was expected to increase ankle plantar flexion or extension, thereby affecting sagittal plane ankle ROM. Such differences may affect the entire lower extremity kinematic chain, resulting in changes in the ROM and/or mean joint angle of the knee and hip as well. Maximum speed and stride rate were identified as potential key indicators of skating performance and efficiency, respectively. While skating efficiency was not directly measured, decreased stride rate at a constant speed likely reflects increased stroke efficiency.

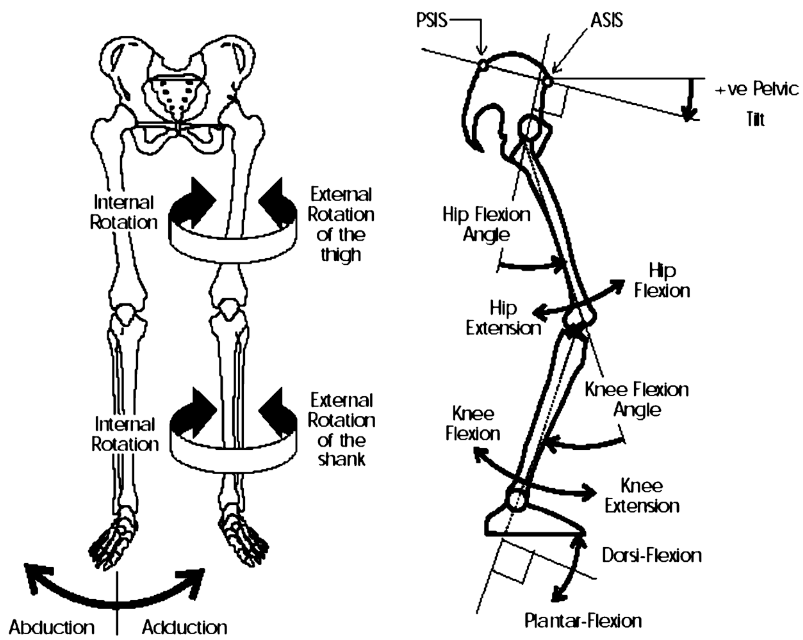

Figure 9. PIG model of the lower extremities and the relative joint angle definitions. Positive angles indicate flexion, dorsi-flexion, adduction, and internal rotation; negative angles indicate extension, plantar flexion, abduction, and external rotation. Adapted from [34].

3.3 DATA ANALYSIS

Marker trajectories were processed using Vicon Nexus (Version 1.8.4, Vicon Motion Systems, Ltd, Oxford, United Kingdom). Limb segments and joint angles were defined based on the standard Vicon Plug-in Gait (PIG) model (Figure 9); event detection and further processing were completed using MATLAB (version R2012b, MathWorks, Natick MA). Training effects were assessed via comparison of session 1 versus 5 data, as well as session 6 versus 10 data. Skate design effects, e.g., Mako versus the non-Mako traditional skate, were assessed via comparison of session 5 versus 6 data, and session 5 versus 10 data for both subject groups.

3.3.1 Kinematic Modeling

Marker motion data from the dynamic trials were processed prior to PIG modeling. Vicon Nexus utilizes direct linear transformation to determine the three-dimensional locations of each marker in each frame in the global coordinate system. Marker trajectory gaps less than 20 frames (0.2s) were interpolated such that marker positions were defined for the entire trial. A general cross validation Woltring filter was applied to smooth marker trajectories. The PIG model defines local limb segment origins and orientations from the individual marker locations and anthropometric measurements (Figure 6). The thigh segment, for example, has its origin at the knee joint center with the z-axis pointing towards the hip joint center and the positive x-axis intersecting the lateral femoral condyle marker. The knee and hip joint centers are virtual markers whose locations were calculated using the measured knee width, ASIS to medial malleolus length, and inter-ASIS distance in conjunction with models developed from averaged, non-pathological anthropometric data [34, 35]. The trunk, pelvis, shank, and foot segments were found in a similar manner. Once the origins and orientations of the individual limbs segments were determined, the relative joint angles of the distal segment relative to the proximal segment were determined via Cardan angle calculations. Joint angle rotations were calculated such that the sagittal (flexion/extension or plantar/dorsiflexion) plane angle was determined first, followed by the coronal (abduction/adduction) and transverse (internal/external rotation) plane angles, respectively.

3.3.2 Skate Cycle Event Detection

Gait cycle events, e.g. foot strike and foot off, were automatically detected based on shank and foot marker trajectories using custom MATLAB code. Foot strike was defined as the instant the heel marker exceeded a vertical acceleration threshold (e.g. 250 cm/s^2) and fell below a minimum height threshold (e.g. 13 cm). Foot off was defined based on marker velocity (e.g. vertical velocity of the toe marker exceeded 45 cm/s and forward velocity of the lateral epicondyle marker exceeded 620 cm/s). The glide phase was defined as the duration in which the skate blade of the stroke foot was in full or partial contact with the treadmill surface; the recovery phase was defined as the duration in which the blade of the stroke foot was not in contact with the ground. Each motion trial was divided into strides or skate cycles such that motion data were normalized to percent skate cycle.

The aforementioned temporal, stride and kinematic metrics of interest were calculated for each skate cycle and averaged across *all* skate cycles in a given session (mean strides per session per leg was greater than 100 for each subject). A typical 15-30 second skating trial captured 10-20 strides on each leg. As stride rate is highly correlated with velocity [14], stride rate comparisons between skates were restricted to trials performed at the *same velocity* in both skates.

3.3.4 Statistical Analysis

Statistical analyses were conducted to address the research objectives and test the respective research hypotheses. As stated previously, the objectives of this study were:

1) to determine whether technique training incorporating a lateral stroke would increase skating speed and skate stroke efficiency and
2) to determine whether a skate boot with increased anterior-posterior flexibility would accommodate a more crouched, ergonomic posture resulting in increased speed and efficiency.

For Objective 1, the following hypothesis were tested:

- $H_{0\text{-}1a}$: There is no difference between a given metric of interest as measured in session 5 vs. session 1.

To confirm that effects due to training were obtained within the first 5 weeks of technique training, the following additional hypothesis was tested:

- $H_{0\text{-}1b}$: There is no difference between a given metric of interest as measured in session 10 vs. session 6.

For Objective 2, the following hypotheses were tested:

- $H_{0\text{-}2a}$: There is no difference in a given metric of interest as measured in sessions 5 and 6 between the Mako and Traditional skate groups.
- $H_{0\text{-}2b}$: There is no difference in a given metric of interest as measured in sessions 5 and 10 between the Mako and Traditional skate groups.

Comparison of session 5 and 6 data investigated the effects of skate type on skating performance; subsequent comparison of session 5 and 10 data assessed whether the initial effects (if any) of switching skate were maintained over time. Significance was investigated using two-tailed paired t-tests (p=0.10) using Minitab (Minitab, Inc, Version 17, State College, PA). Two-tailed tests were chosen as the most conservative option due to the lack of previous research to guide use of a one-tailed analysis.

All paired data comparisons were tested for normality using the Anderson-Darling test. Parametric tests were used to investigate normally distributed metrics; significance was then assessed using a paired t-test (p=0.10) (Minitab, Inc, Version 17, State College, PA).

Results were analyzed with both *a priori* and *post hoc* power analyses using G-Power (Version 3.1.9,2, Dusseldorf, Germany) [36]. *A priori* analyses were conducted to estimate an appropriate sample size for the current study based on prior literature, as well as to estimate sample size for future study power of 0.80 at a 95% confidence level. Additionally, *post hoc* analysis was conducted to determine the current study power at a 90% confidence level.

3.4 SUMMARY

Adolescent, male, hockey players who met the research criteria were recruited to participate in a 10-session skate treadmill training program. Subjects were assigned to either MAKO or TRAD skate groups as determined by their initial skate; subjects switched skates after completing 5 of the 10 training sessions. Temporal, stride and kinematic metric data were evaluated at weeks 1 (baseline: skate 1), 5 (post-training: skate 1), 6 (baseline: skate 2), and 10 (post-acclimation: skate 2) via motion analysis. Skating performance effects due to training were assessed via comparisons of sessions 5 vs. 1 and 10 vs. 6; performance effects due to skate type were assessed via comparisons of MAKO vs. TRAD groups during sessions 5 and 6, and 5 and10.

CHAPTER 4: RESULTS

The kinematic data acquired during sessions 1 (baseline: skate 1), 5 (post-training: skate 1), 6 (baseline: skate 2), and 10 (post-acclimation: skate 2) were analyzed for submaximal speed trials for all subjects who completed the study. These data were used to investigate both potential technique training effects and skate design effects.

To investigate potential kinematic mechanisms responsible for the observed increases in maximum speed between skates, the kinematic data acquired during the maximum speed trials were also analyzed. As the primary purpose of the maximum speed trials was to evaluate the subject's peak speed in the given skate, trials were not repeated if a marker fell off or was obstructed from camera view so as to prevent potential subject fatigue. Such marker drop out resulted in incomplete kinematic data for 8 of the 14 subjects during the maximum speed trials, preventing statistical analysis of skate design effects. Although incomplete, the kinematic data from these maximum speed trials were used to identify potential kinematic mechanisms for the observed differences in peak speed, mechanisms that could be further investigated in future studies.

4.1 SUBJECT CHARACTERISICS

Seventeen male youth hockey players, aged 12-16 years, with 7 or more years prior hockey skating experience volunteered to participate in this study. Subjects with skate treadmill experience during the past year were excluded. Three subjects failed to complete the study due to unrelated injuries (2) and scheduling conflicts (1). Anthropometric data, traditional skate type, and skating history for all test subjects are detailed in Table 1. Subjects participated in 10 training sessions with a mean intersession period of 2.2 weeks. Mean submaximal speed for each subject at each data analysis session is presented in Table 2.

Table 1. Anthropometric data, skate history and training summary for all subjects

Subject	Group	Age (yrs.)	Hockey Experience (yrs.)	Height (cm)	Weight (kg)	Training Duration (wks.)	Trad Skate
1	TRAD[#,1]	14	7	171.5	74.4	30.9	Reebok 14K
2	TRAD[#]	12	8	152.4	42.2	20.3	Graf Ultra G-3
3	TRAD[#]	16	12	177.8	95.3	24.7	Bauer x5.0
4	TRAD	14	8	154.9	38.6	24.0	Reebok 12K
5	TRAD	14	10	168.9	60.3	24.0	Bauer TotalOne
6	TRAD[1]	15	10	179.1	74.8	17.9	Bauer APX
7	TRAD	16	10	177.8	77.1	27.6	Bauer APX2
8	TRAD	14	10	172.7	72.6	20.0	CCM RBZ
9	TRAD[#]	15	11	175.3	61.2	19.0	Bauer x7.0
10	MAKO[#]	15	9	177.8	77.1	25.1	Easton Synergy
11	MAKO	15	13	172.7	68.0	20.7	Easton Synergy
12	MAKO	14	11	170.2	65.8	20.7	Bauer APX
13	MAKO[#]	15	8	180.3	79.4	20.6	Easton Synergy
14	MAKO	15	13	176.5	66.7	19.9	Bauer APX
	Mean±SD	14.6±1	10±1.9	170.3±9.5	64.8±15.6	22.5±3.7	
	[Min,Max]	[12, 16]	[7,13]	[152.4,180.3]	[38.6,95.3]	[17.9,30.8]	

[#] subjects included in Session 5 versus 6 maximum speed trial analysis

[1] Subjects excluded from Session 1 versus 5 analysis

Table 2. Submaximal and maximum speed for all subjects and sessions

Subject	Group	Mean Submaximal Speed				Maximum Speed			
		Session 1	Session 5	Session 6	Session 10	Session 1	Session 5	Session 6	Session 10
1	TRAD	-	4.3	5.3	5.4	5.1	6.3	7.8	8.2
2	TRAD	3.9	4.0	4.1	5.1	5.9	5.8	6.4	7.0
3	TRAD	5.3	5.8	5.6	6.5	7.2	7.6	8.9	8.9
4	TRAD	3.4	4.8	4.7	5.3	4.5	6.5	7.1	7.2
5	TRAD	5.0	5.0	5.4	6.6	8.0	8.1	8.9	8.9
6	TRAD	3.7	4.7	4.7	5.6	5.3	6.3	8.4	8.0
7	TRAD	5.0	5.2	5.4	5.5	7.2	8.2	8.5	8.9
8	TRAD	4.3	5.8	5.4	6.5	7.5	7.2	8.2	8.9
9	TRAD	4.6	5.5	5.8	5.9	7.3	7.3	8.7	8.8
10	MAKO	5.4	6.1	5.9	6.1	8.9	8.9	8.0	8.9
11	MAKO	5.8	6.1	5.4	6.1	8.9	8.9	8.9	8.9
12	MAKO	3.8	4.9	4.7	5.7	7.4	8.3	8.4	8.9
13	MAKO	4.5	5.5	5.9	5.8	8.5	8.9	7.5	8.7
14	MAKO	4.0	6.1	4.8	5.9	7.2	7.9	6.7	7.6
Mean±SD		4.5±0.7	5.3±0.7	5.2±0.5	5.8±0.5	7.1±1.4	7.3±0.9	8.3±0.8	8.4±0.7
[Min,Max]		[3.4,5.8]	[4.0,6.1]	[4.1,5.9]	[5.0,6.6]	[4.5,8.9]	[5.8,8.9]	[6.4,8.9]	[7.0,8.9]

4.2 TECHNIQUE TRAINING EFFECTS

Potential technique training effects after 5 treadmill skating sessions were assessed by analyzing session 1 versus session 5 (skate 1) and session 6 versus session 10 (skate 2) data. The analysis of the baseline (session 1) and post-training (session 5) data in the first skate quantified the effects of initial technique training, which emphasized an alternative skating style promoting a more lateral skating stroke. Analyses were also conducted to quantify potential further technique training effects in the second skate [session 6 (baseline) versus session 10 (post-training)].

4.2.1 Initial Skate: Baseline (Session 1) Versus Post-Training (Session 5)

4.2.1.1 Kinematics

The effects of treadmill training and technique instruction on observed kinematics, as assessed by a comparison of session 1 (baseline) versus session 5 (post-training) data, are summarized in Figure 10 and Tables 3-5. Mean hip, knee and ankle kinematic data are shown in Figure 11 for all subjects normalized to percent skate cycle for skate 1 baseline and post-training sessions. No statistically significant differences in hip ROM were observed in any plane. Knee ROM significantly increased [3.5° (4.6%)] with training in the sagittal plane only. Ankle ROM significantly increased in both the sagittal [3.0° (11.4%)] and coronal [1.30° (21.9%)] planes post-training (Table 3).

Table 3. Training effects analysis of lower extremity ROM (averaged across subjects and trials). Percent difference was normalized with respect to Session 1 or 6 data (baseline: Skate 1 and Skate 2, respectively). Bold text indicates significant difference.

	Session 1 (baseline)	Session 5 (post-training)	Session 1 vs. 5 Difference	Session 6 (baseline)	Session 10 (post-acclimation)	Session 6 vs. 10 Difference
	Mean ± SD	Mean ± SD	Absolute (%)	Mean ± SD	Mean ± SD	Absolute (%)
Lower Extremity ROM						
Hip Sagittal (°)	69.8 ± 8.0	71.3 ± 2.9	1.5 ± 5.7 (2.2)	71.1 ± 9.1	72.2 ± 7.5	1.1 ± 4.8 (0.7)
Hip Coronal (°)	35.1 ± 5.2	36.4 ± 4.8	1.3 ± 3.7 (3.7)	37.7 ± 4.5	38.9 ± 5.8	1.2 ± 3.8 (1.5)
Hip Transverse (°)	24.2 ±6.9	23.3 ± 8.0	-0.9 ± 8.2 (3.6)	26.8 ± 10.3	26.7 ± 8.9	-0.1 ± 8.5 (6.2)
Knee Sagittal (°)**	**74.6 ± 8.5**	**78.1 ± 6.0**	**3.5 ± 5.0 (4.6)**	80.3 ± 6.5	79.5 ± 5.1	-0.9 ± 3.4 (0.7)
Knee Coronal (°)	24.3 ±7.8	24.4 ± 4.8	0.1 ± 6.4 (0.5)	20.9 ± 6.9	19.7 ± 9.1	-1.2 ± 5.0 (2.9)
Knee Transverse (°)	20.7 ± 4.3	20.9 ± 5.1	0.1 ±4.2 (0.5)	22.5 ± 5.3	22.8 ± 4.7	0.2 ± 5.8 (1.3)
Ankle Sagittal (°)**	**26.7 ± 5.1**	**29.7 ± 5.9**	**3.0 ± 4.0 (11.4)**	28.5 ± 5.1	27.4 ± 5.0	-1.0 ± 3.4 (12.1)
Ankle Coronal (°)**	**5.9 ± 2.4**	**7.2 ± 2.4**	**1.3 ± 2.1 (21.9)**	6.9 ± 3.2	5.8 ± 2.6	-1.1 ± 2.5 (16.0)
Ankle Transverse (°)	28.7 ± 8.5	26.4 ± 5.2	-2.3 ± 9.2 (8.0)	26.1 ± 6.8	23.1 ± 6.7	3.0 ± 6.4 (0.6)

**** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$ in session 1 vs. session 5 comparison*
♮♮♮ $p < 0.01$, ♮♮ $p < 0.05$, ♮ $p < 0.10$ in session 6 vs. session 10 comparison

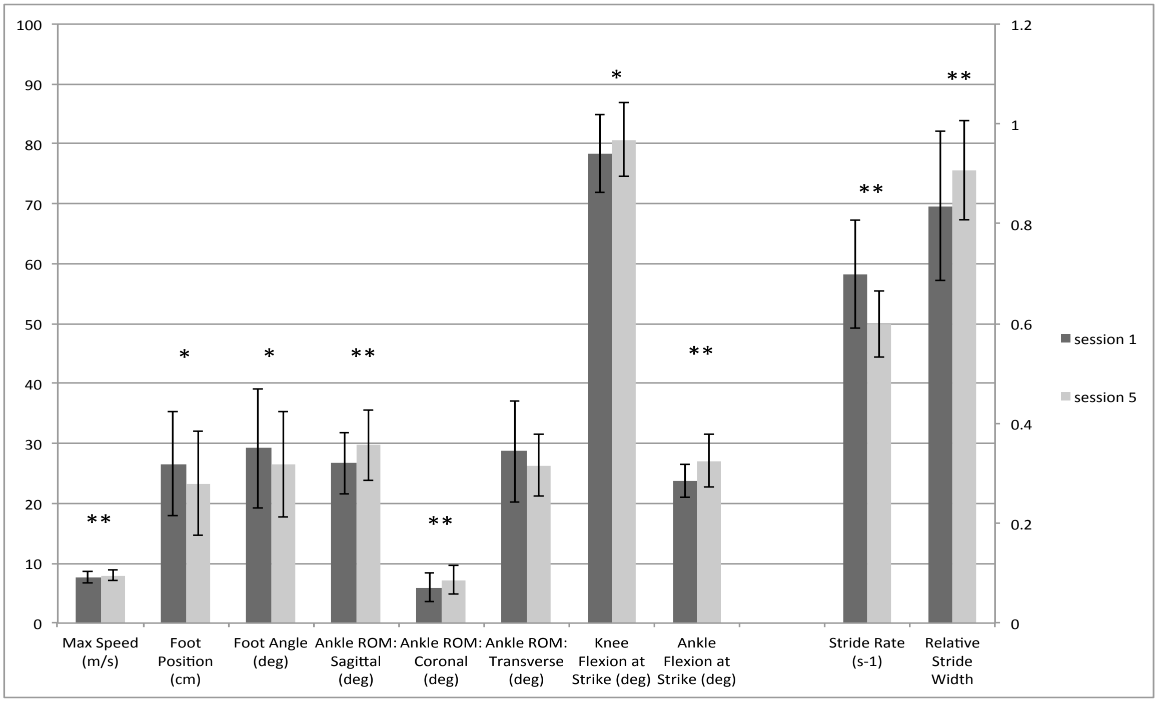

Figure 10. Summary of mean temporal (speed, stride rate), kinematic (segment angles, relative position, ROM, and height) and stride (width) metrics as a function of skate type for submaximal speed trials (N=14). Asterisks indicate significance: *** $p < 0.001$, ** $p < 0.05$, * $p < 0.10$.

Training effects also included significant differences in mean hip, knee and ankle angle (Table 4, Figure 11). Mean knee flexion and ankle dorsiflexion over the skate cycle significantly increased [3.7° (5.4%) and 3.5° (19.0%), respectively] with training. These increases were primarily observed during the glide portion of the skate cycle, reflecting a more crouched posture post-training. In the coronal plane, knee valgus [5.1° (371%)] and ankle inversion [3.0° (76.8%)] also increased throughout the gait cycle post-training. Finally, hip external rotation [4.9° (4480%)], knee internal rotation [14.2° (102%)], and ankle adduction [10.3° (49.8%)] increased with training. The increased ankle inversion and adduction indicate a more supinated foot post-training.

Table 4. Training effects analysis of mean joint angle (averaged across subjects and trials). Percent difference was normalized with respect to Session 1 or 6 data (Baseline, Skate 1 and Skate 2, respectively). Bold text indicates significant difference.

	Session 1 (baseline)	Session 5 (post-training)	Session 1 vs. 5 Difference	Session 6 (baseline)	Session 10 (post-acclimation)	Session 6 vs.10 Difference
	Mean ± SD	Mean ± SD	Absolute (%)	Mean ± SD	Mean ± SD	Absolute (%)
Mean Joint Angle						
Hip Sagittal (°)	63.0 ± 18.4	61.5 ± 16.1	-1.5 ± 14.9 (2.4)	58.6 ± 10.2	60.5 ± 10.1	1.8 ± 10.7 (3.1)
Hip Coronal (°)□□□	-8.0 ± 3.9	-7.8 ± 4.0	0.2 ± 4.1 (2.0)	**-7.5 ± 1.4**	**-9.1 ± 1.6**	**-1.7 ± 1.2 (22.7)**
Hip Transverse (°)***	**0.1 ± 13.1**	**-4.8 ± 10.6**	**-4.9 ± 13.1 (4481.8)**	-1.6 ± 8.6	2.0 ± 6.1	3.6 ± 9.6 (225.0)
Knee Sagittal (°)**	**68.5 ± 8.0**	**72.2 ± 6.1**	**3.7 ± 6.3 (5.4)**	69.1 ± 5.5	68.1 ± 4.4	-1.0 ± 3.6 (1.4)
Knee Coronal (°)**	**1.4 ± 14.9**	**-3.7 ± 12.3**	**-5.1 ± 13.0 (370.8)**	0.3 ± 9.9	4.1 ± 7.0	3.9 ± 9.3 (1300)
Knee Transverse (°)*,□□**	**13.9 ± 13.8**	**28.2 ± 13.5**	**14.2 ± 16.5 (102.4)**	**19.6 ± 8.2**	**14.8 ± 6.1**	**-4.9 ± 7.3 (25.0)**
Ankle Sagittal (°)**	**18.2 ± 4.3**	**21.7 ± 6.7**	**3.5 ± 5.8 (19.0)**	20.3 ± 2.4	20.3 ± 4.1	0.0 ± 3.2 (0.0)
Ankle Coronal (°)***	**3.9 ± 2.2**	**6.9 ± 4.2**	**3.0 ± 3.7 (76.8)**	5.1 ± 2.2	4.2 ± 1.4	-0.9 ± 3.2 (17.6)
Ankle Transverse (°)*,□□**	**-20.7 ± 11.1**	**-31.0 ± 12.8**	**-10.3 ± 13.5 (49.8)**	**-24.2 ± 7.3**	**-20.2 ± 5.2**	**-4.0 ± 7.9 (16.5)**

*** *p < 0.01,* ** *p < 0.05,* * *p < 0.10 in session 1 vs. session 5 comparison*

□□□ *p < 0.01,* □□ *p < 0.05,* □ *p < 0.10 in session 6 vs. session 10 comparison*

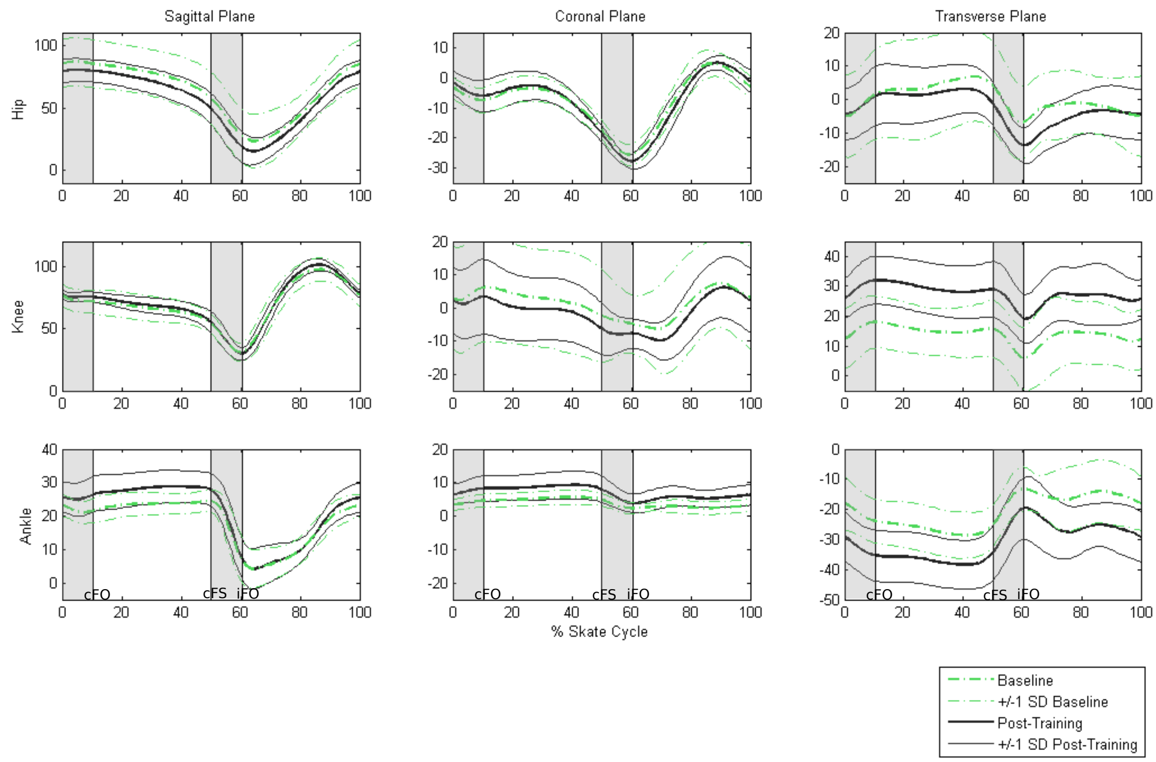

Figure 11. Kinematic effects as a function of technique training. Initial session 1 (dash) vs. session 5 (solid) mean joint angles as a function of skate cycle in each plane for submaximal speed trials (N=12). Positive angles represent flexion/dorsiflexion, adduction and internal rotation. (cFO =contralateral foot off, cFS = contralateral foot strike, iFO = ipsilateral foot off)

As the objective of the alternative skate technique is to improve stroke efficiency or force application during push-off, training effects were also contrasted during foot strike and foot-off events (Table 5). Despite significantly increased knee flexion at foot strike with training, no significant difference in the relative sacral height was observed. Relative anterior-posterior foot position and foot outset angle both decreased significantly [3.23cm (12.2%) and 2.7° (9.3%), respectively] at foot-off post-training.

Table 5. Training effects analysis of foot-strike and foot-off metrics (averaged across subjects and trials). Percent difference was normalized with respect to Session 1 or 6 data (baseline: Skate 1 and Skate 2, respectively). Bold text indicates significant difference.

	Session 1 (baseline)	Session 5 (post-training)	Session 1 vs. 5 Difference	Session 6 (baseline)	Session 10 (post-acclimation)	Session 6 vs. 10 Difference
	Mean ± SD	Mean ± SD	Absolute (%)	Mean ± SD	Mean ± SD	Absolute (%)
Sagittal Position at Foot-Strike						
Sacral Height (relative to standing sacral height) □□□	0.84 ± 0.02	0.84 ± 0.03	0.0 ± 0.2 (-0.4)	**0.85 ± 0.03**	**0.83 ± 0.03**	**-0.02 ± 0.02 (2.4)**
Hip Angle (°)	87.0 ± 18.8	84.9 ± 17.6	-2.0 ± 14.8 (-2.4)	81.6 ± 10.2	83.7 ± 8.8	2.1 ± 10.3 (2.6)
Knee Angle (°)**	**78.4 ± 6.5**	**80.7 ± 6.1**	**2.3 ± 4.6 (3.0)**	77.4 ± 6.4	76.7 ± 6.0	-0.7 ± 3.1 (0.9)
Ankle Angle (°)	28.7 ± 8.5	26.4 ± 5.2	-2.3 ± 3.8 (-8.0)	24.5 ± 3.5	25.3 ± 5.0	0.8 ± 3.5 (3.2)
Torso Angle (°)□□□	38.2 ± 13.3	42.7 ± 9.7	4.5 ± 11.7 (11.8)	**47.2 ± 7.4**	**30.4 ± 19.5**	**-16.7 ± 20.3 (35.4)**
Spine Angle (°)□□□	13.0 ± 14.2	17.3 ± 13.3	4.3 ± 14.5 (33.1)	**18.8 ± 11.4**	**12.8 ± 14.2**	**-5.9 ± 6.8 (31.4)**
Foot Position at Foot-Off						
Foot Position (cm)*	**26.6 ± 9.2**	**23.3 ± 8.7**	**-3.2 ± 6.9 (-12.2)**	22.5 ± 7.1	24.7 ± 8.2	2.1 ± 8.2 (-4.6)
Foot Angle (°)*	**29.2 ± 10.0**	**26.5 ± 8.8**	**-2.7 ± 6.7 (-9.3)**	27.1 ± 6.0	28.5 ± 7.0	1.33 ± 6.2 (-6.5)

**** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$ in session 1 vs. session 5 comparison*
□□□ $p < 0.01$, □□ $p < 0.05$, □ $p < 0.10$ in session 6 vs. session 10 comparison

Table 6. Training effects analysis of temporal and stride metrics (averaged across subjects and trials). Percent difference was normalized with respect to Session 1 or 6 data (Baseline, Skate 1 and Skate 2, respectively). Bold text indicates significant difference.

	Session 1 (baseline)	**Session 5 (post-training)**	**Session 1 vs. 5 Difference**	**Session 6 (baseline)**	**Session 10 (post-acclimation)**	**Session 6 ves10 Difference**
	Mean ± SD	Mean ± SD	Absolute (%)	Mean ± SD	Mean ± SD	Absolute (%)
Temporal and Stride Metrics						
Maximum Speed (m/s), □□□**	**7.1 ± 1.1**	**7.6 ± 0.9**	**0.5 ± 0.7 (7.9)**	**8.0 ± 0.9**	**8.4 ± 0.7**	**0.4 ± 0.5 (5.1)**
Stride Rate (1/s)*, □□**	**0.70 ± 0.11**	**0.60 ± 0.66**	**-0.10 ± 0.11 (-14.3)**	**0.60 ± 0.04**	**0.67 ± 0.10**	**0.07 ± 0.06 (-11.7)**
Glide Duration (% cycle)	60.5 ± 2.5	60.6 ± 1.8	0.00 ± 2.4 (0.1)	60.4 ± 1.9	60.5 ± 1.6	0.01 ± 0.1 (0.02)
Single Support (% cycle)	78.9 ± 4.9	78.9 ± 6.9	-0.1 ± 6.0 (-0.1)	79.2 ± 3.8	80.2 ± 7.4	1.1 ± 0.06 (1.4)
Stride Width (cm)***	**141.8 ± 29.3**	**155.9± 19.0**	**14.1 ± 16.8 (9.9)**	156.3 ± 15.8	157.6 ± 20.8	1.3 ± 19.7 (0.8)

*** *$p < 0.01$, ** $p < 0.05$, * $p < 0.10$ in session 1 vs. session 5 comparison*

□□□ *$p < 0.01$,* □□ *$p < 0.05$,* □ *$p < 0.10$ in session 6 vs. session 10 comparison*

4.2.1.2 Temporal and Stride Characteristics

The effects of technique instruction on temporal and stride metrics are summarized in Table 6 and Figure 10. Maximum speed significantly increased [0.53m/s (7.5%)] with technique training. These speed increases had a ceiling effect, however, as three subjects (10, 11, and 13) were able to skate at the maximal treadmill speed (8.94 m/s) post-training. Two of these subjects (10 and 11) were able to skate at 8.94 m/s at both baseline and post-training sessions; the effect of technique training on maximum speed could therefore not be assessed for these subjects, and data from these subjects were excluded from the statistical analyses. Stride width also increased [14.1cm (8.5%)] significantly post-training, regardless of skate type. Stride rate, as assessed during a subset of trials in which the treadmill speed was constant, decreased [0.10 strides/s (approximately 14%)] significantly post-training. No significant differences in glide versus recovery or single versus double support durations were observed post-training.

4.2.2 Skate 2: Baseline (Session 6) Versus Post-Training (Session 10)

4.2.2.1 Kinematics

The kinematic post-training effects in the second skate are summarized in Tables 3-5. Mean hip, knee and ankle kinematic data are shown in Figure 12 for all subjects, again normalized to percent skate cycle for both sessions. Subjects displayed significant decreases in relative sacral height [0.2 (2.4%)], torso angle [16.7° (35.4%)], and spine angle [5.9° (31.4%)] (Table 5). While the mean relative sacral height, torso angle, and spine angle all decreased significantly between sessions 6 through 10, the final value of each of these metrics in session 5 and session 10 are comparable suggesting that this was not a continued training effect, but rather an effect of subjects having an increased relative sacral height, torso angle, and spine angle in session six (the first session in the new skate). No other significant differences in kinematic metrics were observed in the post-training analysis with skate 2.

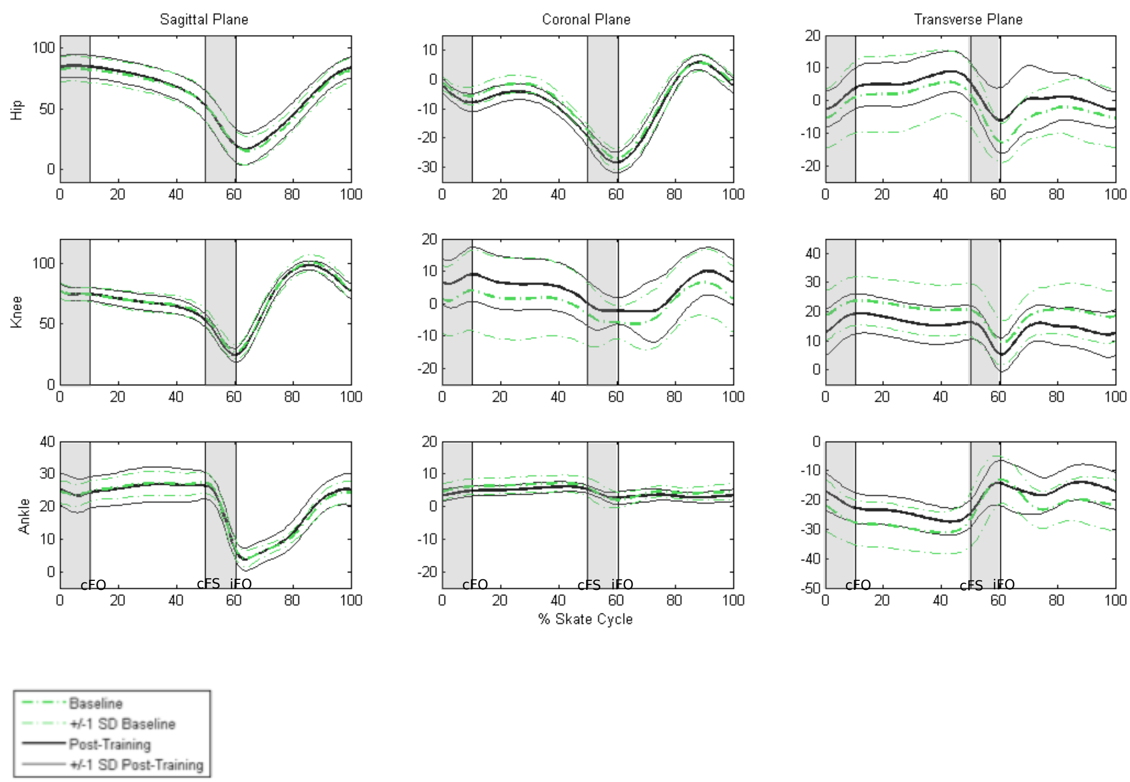

Figure 12. Kinematic effects as a function of technique training with skate 2. Session 6 (dash) vs. session 10 (solid) mean joint angles as a function of skate cycle in each plane for submaximal speed trials (N=12). Positive angles represent flexion/dorsiflexion, adduction and internal rotation. (cFO =contralateral foot off, cFS = contralateral foot strike, iFO = ipsilateral foot off)

4.2.2.2 Temporal and Stride Characteristics

Temporal and stride metrics after five technique training sessions in the second skate are summarized in Table 6. Similar to the training effects observed with skate 1, maximum speed significantly increased [0.41m/s (5.1%)], indicating that subjects continued to increase speed after session 5. These speed increases were again subject to a ceiling effect. By session 10, seven subjects (3, 5, 7, 8, 10, 11, and 12) were able to skate at the maximal treadmill speed (8.94 m/s). Three of these subjects (3, 5, and 11) were able to skate at 8.94 m/s at both session 6 and 10; the effect of additional potential technique training and/or treadmill acclimation on maximum speed could therefore not be assessed for these subjects. Stride rate, as assessed during constant speed trials, decreased [0.07 strides/s (11.7%)] significantly. As for maximum speed analysis, the significantly reduced stride rate indicates that this metric continued to vary beyond session 5. No significant differences in stride width, glide versus recovery, or single versus double support durations were observed.

4.3 SKATE EFFECTS

The effects of skate design on skating performance were analyzed by comparing post-technique training data. Initial skate effects were contrasted using session 5 (skate 1) and session 6 (skate 2) data and are summarized in Figure 10. To assess whether such potential skate effects were enhanced or faded with subsequent technique training and prolonged use of skate 2, session 5 (skate 1) data were also contrasted with session 10 (skate 2) data.

4.3.1 Initial Effects: Traditional Skate Versus Mako Skate (Sessions 5 and 6)

4.3.1.1 Kinematics

Average hip, knee and ankle kinematic data for all subjects in both skates for the submaximal speed trials are shown in Figure 13a; similar data for the maximum speed trials are shown in Figure 13b for the subset of subjects who did not achieve the peak treadmill speed (e.g. no ceiling effects) and for whom kinematic data were complete. As shown by the aggregate data in Table 7, no significant differences between skates were observed in either hip or knee ROM in any plane during the submaximal speed trials. Although ankle ROM did not vary with skate in the transverse plane, significant decreases in ankle ROM were observed in both the sagittal [3.8° (12.1%)] and coronal [1.2° (16.0%)] planes with the Mako skate for the submaximal speed trials. These differences in sagittal plane ankle motion with skate design are illustrated as a function of skate cycle in Figure 14a and 14b for the submaximal and maximal speed trials, respectively. Differences in ankle motion were observed during the glide (0 to ~60% skate cycle) and recovery (~60 to 100% skate cycle) phases for both the submaximal and maximum speed trials. Significant differences in mean joint angle included a significant decrease in coronal ankle angle (-1.7°) and a significant increase in transverse ankle angle (5.6°) with the Mako skate during submaximal trials (Table 8).

The kinematic effects of skate design during the submaximal speed trials were also investigated at foot strike and foot-off (Table 9). No significant differences in mean ankle, knee, hip, or torso flexion angle at foot strike were observed between skates. Consequently, no statistically significant difference in the relative sacral height was observed at foot strike between skates. Although no significant difference in torso angle was observed, the spine angle increased [4.9° (31.7%)] significantly at foot-off when skating at submaximal speeds in the Mako skate, reflecting increased posterior pelvic tilt with the Mako skate. No significant differences were observed in foot positioning or foot angle at foot-off.

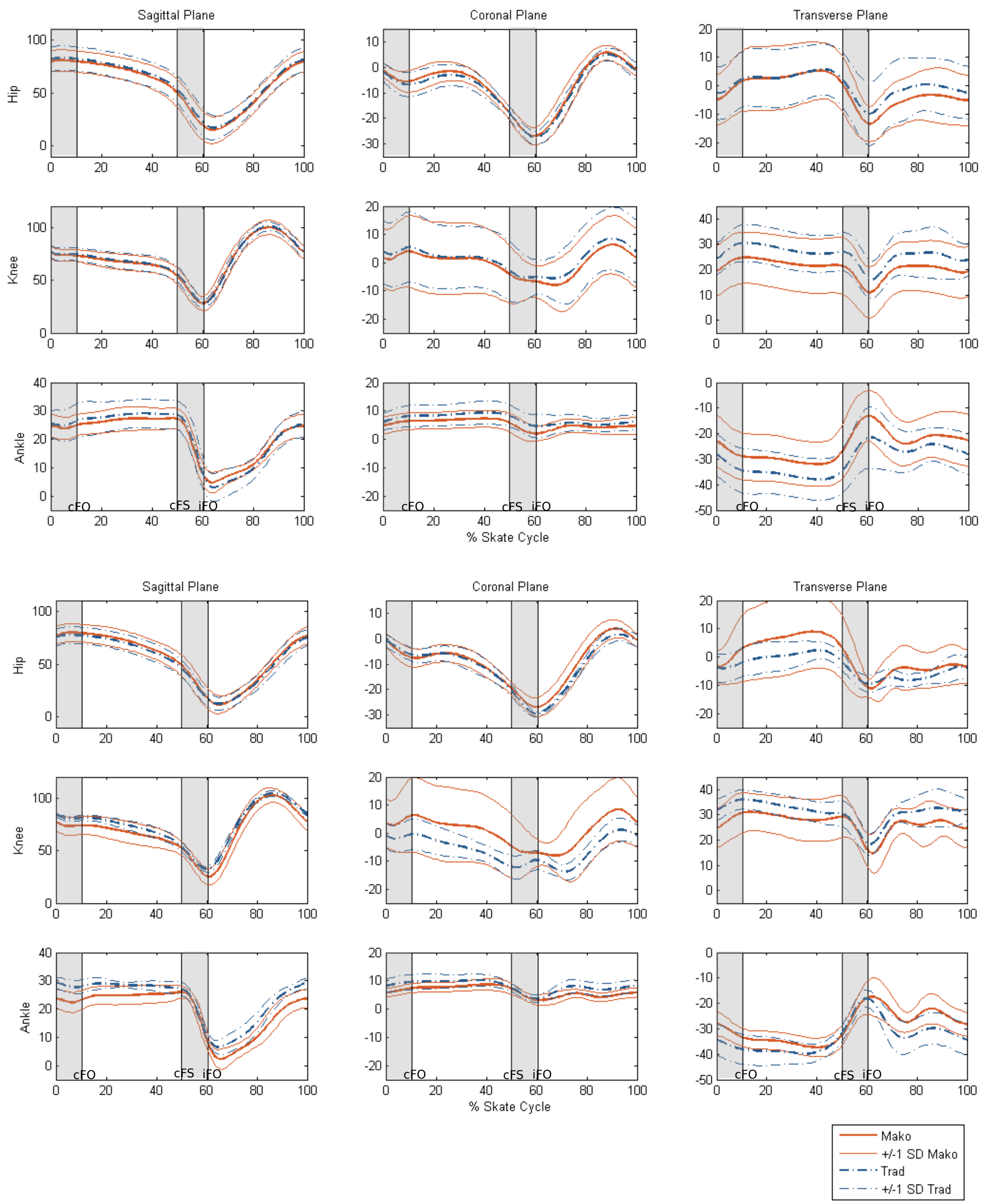

Figure 13. Kinematic effects as a function of skate design. Mean joint angles as a function of skate cycle in each plane for submaximal speed trials (N=14) (top) and maximum speed trials (N=6) (bottom). Positive angles represent flexion/dorsiflexion, adduction and internal rotation. (cFO =contralateral foot off, cFS = contralateral foot strike, iFO = ipsilateral foot off)

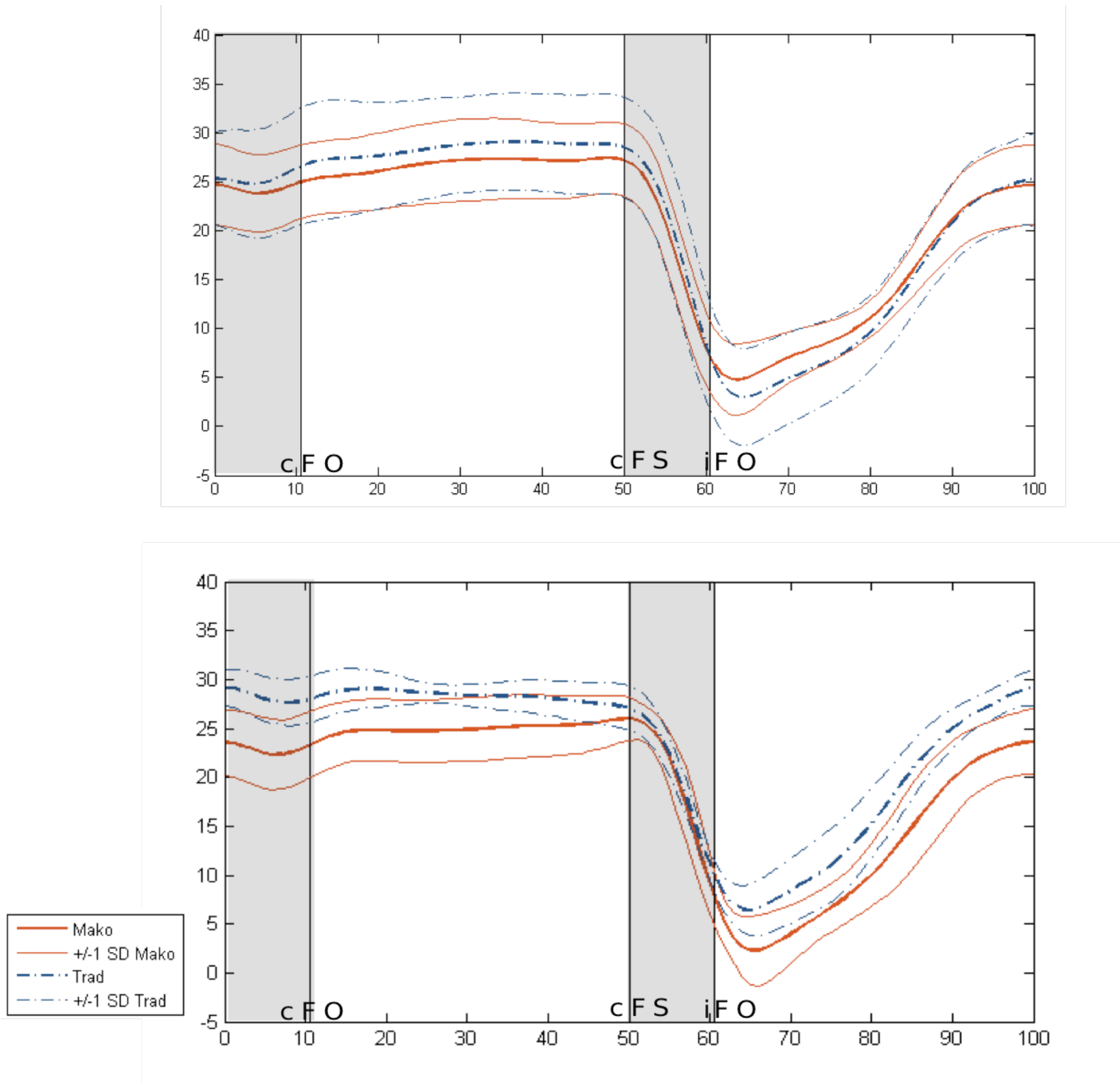

Figure 14. Ankle kinematic effects as a function of skate design. Mean sagittal plane ankle motion (+dorsiflexion) across subjects as a function of skate cycle for the traditional and Mako skates for (top) submaximal speed trials (N=14) and (bottom) maximum speed trials (N=6). (cFO =contralateral foot off, cFS = contralateral foot strike, iFO = ipsilateral foot off)

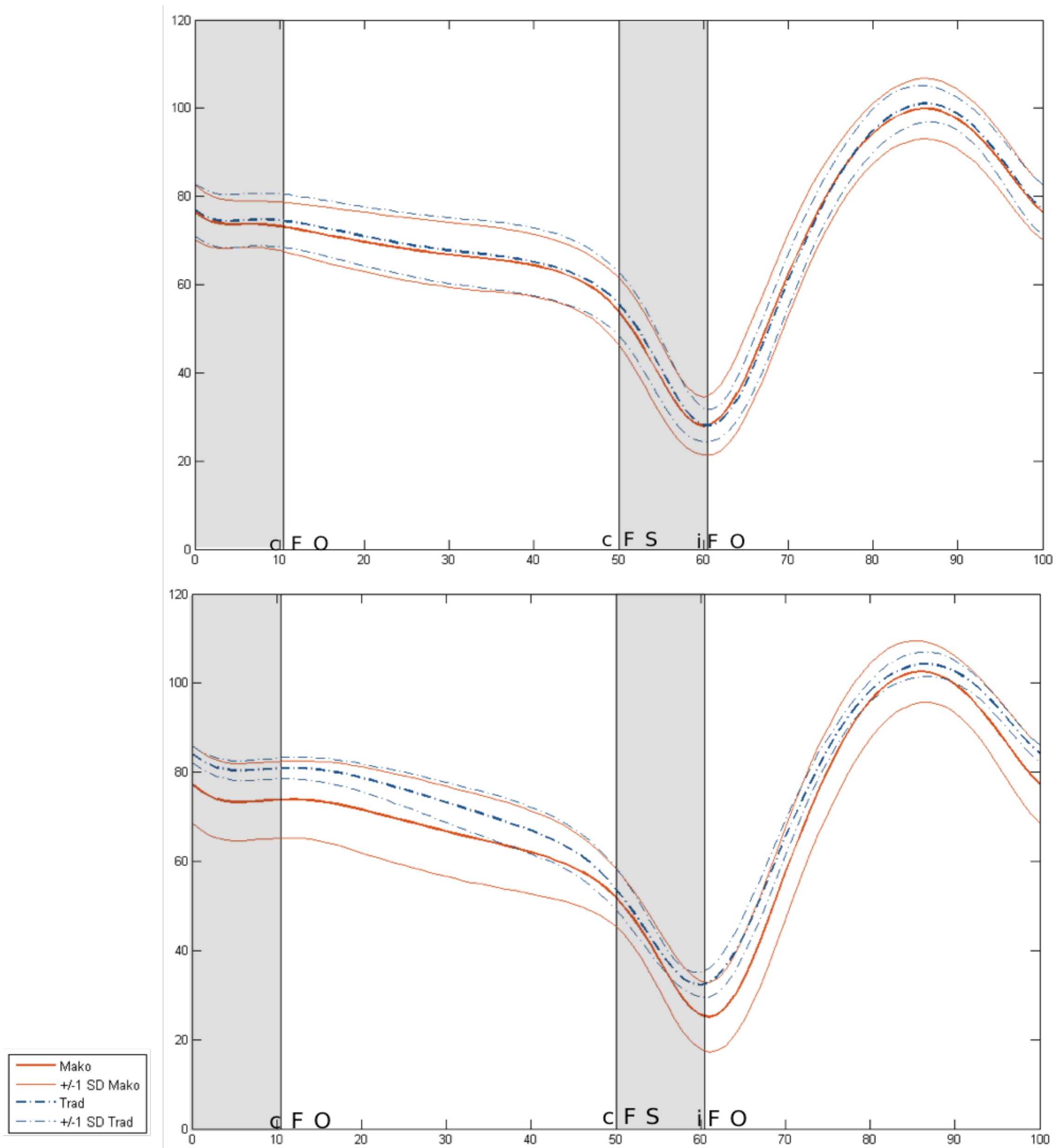

Figure 15. Knee kinematic effects as a function of skate design. Mean sagittal plane knee motion (+flexion) is also shown for the submaximal speed trials (top) and maximum speed trials (bottom). (cFO =contralateral foot off, cFS = contralateral foot strike, iFO = ipsilateral foot off)

Table 7. Analysis of lower extremity ROM (averaged across subjects and trials) as a function of skate design during submaximal trials. Percent difference was normalized with respect to TRAD data. Bold text indicates significant difference.

	Session 5 and 6			Sessions 5 and 10		
	TRAD	**MAKO**	**Difference**	**TRAD**	**MAKO**	**Difference**
	Mean ± SD	Mean ± SD	Absolute (%)	Mean ± SD	Mean ± SD	Absolute (%)
Lower Extremity ROM						
Hip Sagittal (°)	70.2 ± 9.9	69.7 ± 9.3	-0.5 ± 6.9 (0.7)	71.1 ± 9.1	72.2 ± 7.5	1.1 ± 6.2 (0.7)
Hip Coronal (°)	36.6 ± 5.6	37.1 ± 3.4	0.5 ± 3.0 (1.5)	37.7 ± 4.5	38.9 ± 5.8	1.2 ± 5.1 (1.5)
Hip Transverse (°)	25.9 ± 8.2	24.3 ± 7.8	-1.6 ± 5.4 (6.2)	24.9 ± 8.2	26.4 ± 8.0	1.5 ± 6.2 (6.2)
Knee Sagittal (°)	79.8 ± 5.5	79.2 ± 7.0	-0.6 ± 4.7 (0.7)	79.9 ± 5.4	78.1 ± 5.5	-1.8 ± 4.7 (1.4)
Knee Coronal (°)	23.0 ± 5.2	23.7 ± 5.2	0.7 ± 5.1 (2.9)	24.4 ± 5.0	22.3 ± 4.6	-2.1 ± 5.4 (8.1)
Knee Transverse (°)	21.6 ± 6.3	21.8 ± 7.4	0.2 ± 8.8 (1.3)	21.1 ± 7.1	21.3 ± 9.2	0.2 ± 10.3 (1.3)
Ankle Sagittal (°),□□**	**31.4 ± 5.8**	**27.6 ± 5.3**	**-3.8 ± 5.5 (12.1)**	**30.6 ± 6.2**	**27.2 ± 5.2**	**-3.4 ± 5.4 (11.1)**
Ankle Coronal (°)*	**7.5 ± 2.8**	**6.3 ± 2.5**	**-1.2 ± 2.7 (16.0)**	7.4 ± 3.1	6.0 ± 2.4	-1.4 ± 3.2 (18.9)
Ankle Transverse (°)	25.5 ± 7.0	26.3 ± 4.4	0.8 ± 6.6 (3.9)	23.7 ± 5.0	25.1 ± 6.7	1.4 ± 8.7 (5.9)

**** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$ in session 5 and 6 comparison of TRAD vs. MAKO*

□□□ $p < 0.01$, □□ $p < 0.05$, □ $p < 0.10$ in session 5 and 10 comparison of TRAD vs. MAKO

Table 8. Analysis of mean joint angle (averaged across subjects and trials) as a function of skate design during submaximal trials. Percent difference was normalized with respect to TRAD data. Bold text indicates significant difference.

	Session 5 and 6			Sessions 5 and 10		
	TRAD	**MAKO**	**Difference**	**TRAD**	**MAKO**	**Difference**
	Mean ± SD	Mean ± SD	Absolute (%)	Mean ± SD	Mean ± SD	Absolute (%)
Mean Joint Angle						
Hip Sagittal (°)	59.0 ± 10.7	56.8 ± 10.2	-2.2 ± 10.8 (3.7)	58.7 ± 10.9	58.9 ± 10.2	0.2 ± 12.1 (0.3)
Hip Coronal (°)	-8.4 ± 2.2	-7.4 ± 2.1	1.0 ± 2.3 (11.9)	-8.7 ± 2.0	-8.7 ± 2.4	0.0 ± 2.7 (0.0)
Hip Transverse (°)	0.0 ± 9.3	-2.0 ± 8.8	-2.0 ± 9.3 (100.0)	1.3 ± 8.6	0.4 ± 7.4	-0.9 ± 8.3 (69.2)
Knee Sagittal (°)□	69.5 ± 4.2	68.8 ± 5.5	-0.7 ± 2.9 (1.0)	**69.6 ± 4.1**	**67.7 ± 4.4**	**-1.9 ± 3.3 (2.7)**
Knee Coronal (°)	1.3 ± 10.2	-0.3 ± 10.3	-1.6 ± 9.2 (123.1)	2.4 ± 9.6	2.4 ± 8.7	0.0 ± 9.4 (0.0)
Knee Transverse (°)	25.9 ± 7.5	20.6 ± 9.9	-5.2 ± 11.8 (20.9)	23.9 ± 9.4	17.7 ± 9.0	-6.2 ± 15.4 (25.9)
Ankle Sagittal (°)	21.0 ± 4.4	20.5 ± 3.0	-0.5 ± 5.3 (2.4)	21.6 ± 4.9	19.9 ± 3.7	-1.8 ± 6.8 (8.3)
Ankle Coronal (°)*,□	**7.0 ± 3.3**	**5.3 ± 2.7**	**-1.7 ± 3.4 (24.2)**	**6.7 ± 3.6**	**4.6 ± 2.0**	**-2.1 ± 4.4 (31.3)**
Ankle Transverse (°)*	**-30.5 ± 8.2**	**-24.9 ± 9.0**	**5.6 ± 11.1 (18.4)**	-28.9 ± 10.1	-22.6 ± 7.4	6.2 ± 13.7 (21.4)

**** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$ in session 5 and 6 comparison of TRAD vs. MAKO*

□□□ $p < 0.01$, □□ $p < 0.05$, □ $p < 0.10$ in session 5 and 10 comparison of TRAD vs. MAKO

Table 9. Analysis of foot-strike and foot-off metrics (averaged across subjects and trials) as a function of skate design during submaximal trials. Percent difference was normalized with respect to TRAD data. Bold text indicates significant difference.

	Session 5 and 6			Sessions 5 and 10		
	TRAD	**MAKO**	**Difference**	**TRAD**	**MAKO**	**Difference**
	Mean ± SD	Mean ± SD	Absolute (%)	Mean ± SD	Mean ± SD	Absolute (%)
Sagittal Position at Foot-Strike						
Sacral Height (relative to standing sacral height)	0.85 ± 0.03	0.85 ± 0.04	0.0 ± 0.03 (0.0)	0.84 ± 0.03	0.84 ± 0.03	0.00 ± 0.02 (0.0)
Hip Angle (°)	79.3 ± 9.8	81.3 ± 11.2	2.0 ± 11.2 (2.5)	81.6 ± 8.8	81.0 ± 1.3	-0.6 ± 12.3 (0.7)
Knee Angle (°)	77.0 ± 5.9	76.5 ± 6.2	-0.5 ± 4.1 (0.6)	75.7 ± 5.6	77.0 ± 5.9	1.3 ± 3.9 (1.6)
Ankle Angle (°)	24.7 ± 4.1	25.3 ± 4.7	0.6 ± 5.7 (8.0)	24.5 ± 3.5	25.3 ± 5.0	0.8 ± 3.5 (3.2)
Torso Angle (°)	42.6 ± 9.6	45.9 ± 7.7	3.3 ± 12.6 (10.5)	35.1 ± 15.2	36.9 ± 17.4	1.8 ± 23.6 (2.3)
Spine Angle (°)*	**15.4 ± 10.0**	**20.3 ± 13.4**	**4.9 ± 13.2 (31.7)**	13.7 ± 11.1	14.5 ± 16.7	0.8 ± 14.9 (5.1)
Foot Position at Foot-Off						
Foot Position (cm)	23.5 ± 8.7	22.4 ± 7.9	-1.1 ± 7.2 (4.6)	23.7 ± 10.0	24.6 ± 7.7	0.9 ± 8.5 (3.4)
Foot Angle (°)	28.2 ± 8.9	26.4 ± 7.4	-1.8 ± 6.5 (6.5)	28.2 ± 9.9	27.7 ± 7.0	-0.5 ± 8.1 (1.8)

*** *$p < 0.01$, ** $p < 0.05$, * $p < 0.10$ in session 5 and 6 comparison of TRAD vs. MAKO*

□□□ *$p < 0.01$, □□ $p < 0.05$, □ $p < 0.10$ in session 5 and 10 comparison of TRAD vs. MAKO*

4.3.1.2 Temporal and Stride Characteristics

The effect of skate design on temporal and stride metrics are summarized in Table 10 and Figure 16. Maximum speed increased nearly 13% (1.0m/s) for subjects wearing the Mako versus traditional skate. Greater increases in peak speed may have been possible, however, as four subjects (3, 5, 10, 13) were able to skate at the maximal treadmill speed (8.9 m/s) in the Mako skate. One additional subject (11) was able to skate at 8.9 m/s in both the Mako and traditional skates; the effect of skate design on maximum speed therefore could not be assessed for this subject. Despite comparable mean submaximal speed with both skates (Table 2), significant increases in stride width and rate [4.7cm (3%) and 0.04 strides/s (6%), respectively] were observed for subjects skating in the Mako skate. No significant differences in glide versus recovery or single versus double support durations were observed between skate designs during the submaximal speed trials.

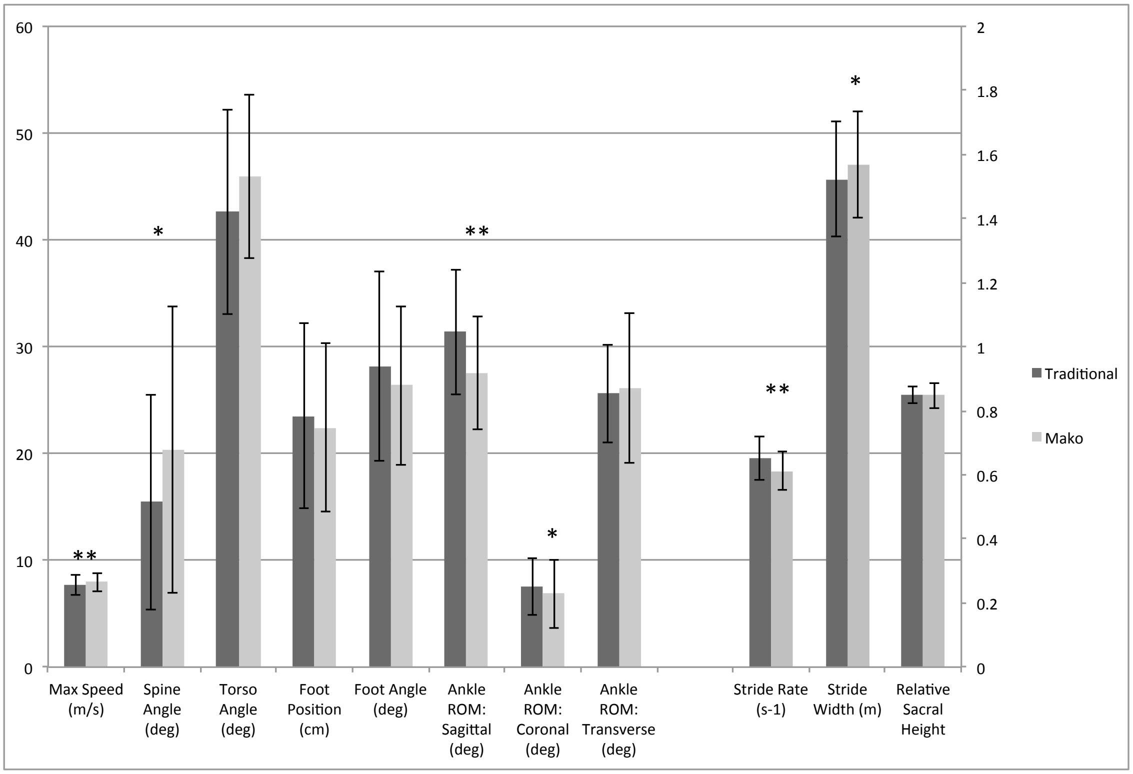

Figure 16. Summary of mean temporal (speed, stride rate), kinematic (segment angles, relative position, ROM, and height) and stride (width) metrics as a function of skate design for submaximal and maximum speed trials (N=14). Asterisks indicate significance: *** $p < 0.001$, ** $p < 0.05$, * $p < 0.10$.

4.3.2 Post-Acclimation Skate Effects: Traditional Skate Versus Mako Skate (Sessions 5 and 10)

4.3.2.1 Kinematics

The kinematic effects observed during sessions 5 and 10 are summarized in Tables 7-9. Mean hip, knee and ankle kinematic data are shown in Figure 17 for all subjects, normalized to percent skate cycle for both sessions. For all kinematic metrics analyzed, the only significant differences observed were a decrease [3.4° (11%)] in sagittal plane ankle ROM with the Mako skate, (comparable to the 3.8° observed between skates during session 5 and 6 analysis, Table 7), and significant decreases in mean sagittal plane knee angle [1.9° (2.7%)] and mean coronal plane ankle angle [2.1° (31.3%)].

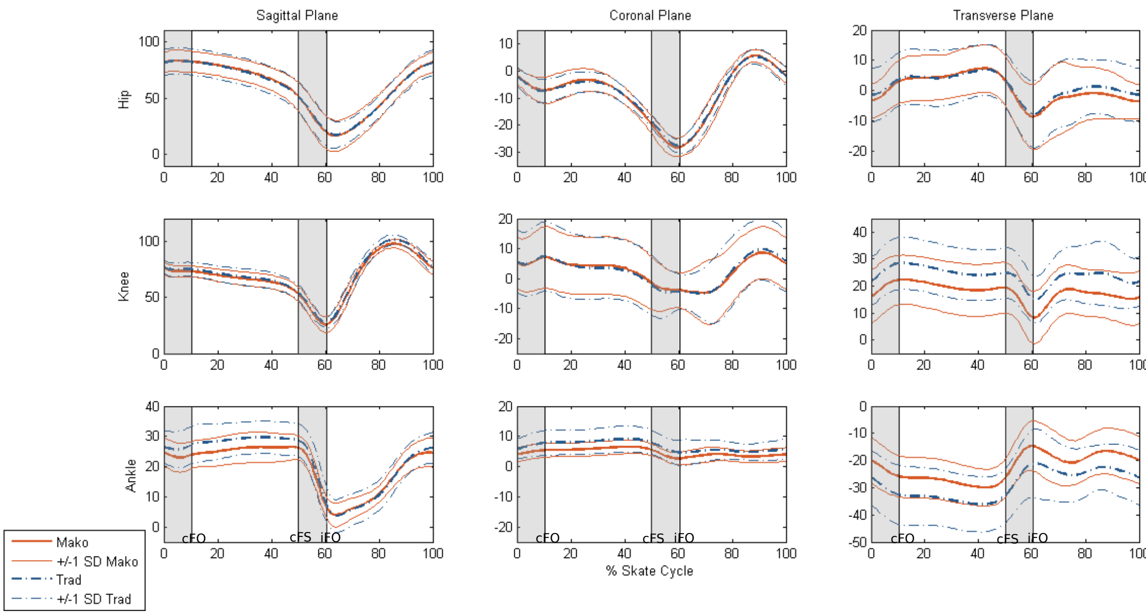

Figure 17. Knee kinematic effects as a function of skate design post-acclimation (sessions 5 and 10): Mako (solid) vs. Traditional (dash). Mean joint angles as a function of skate cycle in each plane for submaximal speed trials (N=12). Positive angles represent flexion/dorsiflexion, adduction and internal rotation. (cFO =contralateral foot off, cFS = contralateral foot strike, iFO = ipsilateral foot off)

4.3.2.2 Temporal and Stride Characteristics

Temporal and stride metrics were also contrasted between skates during sessions 5 and 10 (Table 10). Maximum speed significantly increased [0.82 m/s (10.8%)]. This increase is less than that observed in the initial skate effects analysis. However, these speed increases were again subject to a ceiling effect and further sample size reductions. By session 10, seven subjects (3, 5, 7, 8, 10, 11, and 12) were able to skate at the maximal treadmill speed (8.9m/s). Two of these subjects (11 and 12) were able to skate at 8.9 m/s during both sessions 5 and 10; the effect of additional training/acclimation on maximum speed could only be assessed for five subjects. No other significant differences in stride rate, stride width, glide versus recovery, or single versus double support durations were observed during the submaximal speed trials. Mean stride rate and stride width remained consistent with values observed in session 6, however, there was greater parameter variability in the session 5 and 10 results, contributing to the lack of significance.

Table 10. Analysis of temporal and stride metrics (averaged across subjects and trials) as a function of skate design during submaximal and maximum speed trials. Percent difference was normalized with respect to TRAD data. Bold text indicates significant difference.

	Session 5 and 6			Sessions 5 and 10		
	TRAD	**MAKO**	**Difference**	**TRAD**	**MAKO**	**Difference**
	Mean ± SD	Mean ± SD	Absolute (%)	Mean ± SD	Mean ± SD	Absolute (%)
Temporal and Stride Metrics						
Maximum Speed (m/s)*, □□□**	**7.3 ± 0.9**	**8.3 ± 0.8**	**1.0 ± 0.6 (13.0)**	**7.6 ± 1.0**	**8.4 ± 0.7**	**0.8 ± 0.5 (10.8)**
Stride Rate (1/s)**	**0.65 ± 0.07**	**0.61 ± 0.06**	**-0.04 ± 0.06 (6.2)**	0.64 ± 0.10	0.62 ± 0.07	-0.02 ± 0.10 (6.2)
Glide Duration (% cycle)	60.6 ± 1.9	60.4 ± 2.4	-0.2 ± 1.2 (0.3)	60.7 ± 1.9	60.5 ± 2.2	-0.02 ± 0.1 (0.3)
Single Support (% cycle)	78.9 ± 5.1	79.2 ± 6.5	0.3 ± 3.0 (1.5)	79.6 ± 7.9	78.8 ± 4.3	-0.8 ± 0.1 (1.5)
Stride Width (cm)*	**152.3 ± 18.0**	**157.0 ± 16.7**	**4.6 ± 11.5 (3.0)**	153.0 ± 22.1	158.0 ± 17.4	5.0 ± 17.1 (3.0)

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$ *in session 5 and 6 comparison of TRAD vs. MAKO*

□□□ $p < 0.01$, □□ $p < 0.05$, □ $p < 0.10$ *in session 5 and 10 comparison of TRAD vs. MAKO*

4.4 POWER ANALYSIS

4.4.1 Sample Size Estimation

A priori power analysis was conducted to estimate the required sample size for various effect sizes. Technique training metrics in the literature included stride width and maximum speed. For the skate design analyses, literature data included sagittal plane ankle ROM and maximum speed. Requisite sample sizes for 90% and 95% confidence levels at small (0.2), medium (0.4), and large (0.8) effect sizes are reported in Table 11. These analyses indicate that at least 12 subjects are needed to observe large effect sizes, justifying the study protocol that included recruitment of 17 subjects.

Table 11: *A priori* power analysis to estimate the required sample size for p = 0.05 and p = 0.10. The corresponding changes in maximum speed, stride width, and sagittal plane ankle ROM for each effect size are also presented.

Effect Size	Number of Subjects (p = 0.1)	Number of Subjects (p = 0.05)	Maximum Speed (m/s)	Stride Width (cm)	Sagittal Plane Ankle ROM (degrees)
0.2	114	156	0.1	1.7-6.0	0.7-2.0
0.4	30	41	0.2	3.5-12.7	1.4-4.0
0.8	8	12	0.4	7.0-25.0	2.8-8.0

4.4.2 A Priori Analysis

Power analyses were also conducted for all study metrics at the 95% confidence level ($p < 0.05$) and 80% power to estimate sample sizes for future studies (see Appendix A: Tables A1-A2). Many metrics demonstrated effect sizes that necessitate investigation with 30-50 subjects, assuming that the observed effect sizes for 12-16 year old subjects during treadmill skating are representative.

4.4.3 Post Hoc Analysis

Post hoc power analysis was conducted to assess the associated power of the study metrics (see Appendix, Table A1-A2). Many metrics demonstrated small effect sizes, and were therefore underpowered for the study sample size. For $p = 0.05$ (rather than $p=0.10$ as assumed during study design), many metrics that demonstrated significant differences appear underpowered. The current study design ($n=14$) supports detection of significant ($p < 0.05$) differences with sufficient power ($P = 0.80$) for an effect size ≥ 0.7.

4.5 SUMMARY

Data to investigate both technique training and skate design effects on kinematics, temporal and stride metrics were collected for 14 subjects who completed a 10-session technique training program on a skating treadmill.

Technique training effects were assessed by contrasting baseline and post-training data in each skate. With skate 1, subjects significantly increased stride width and decreased foot separation and outset angle at foot-off, consistent with the alternative technique. Such effects were not subsequently observed with skate 2, indicating that technique training effects equilibrated after five training sessions and that a change of skate did not affect technique.

The effect of skate design was investigated by contrasting kinematic, temporal and stride data during treadmill skating in a traditional skate versus Mako skate. Initial skate effects were identified and re-assessed after further acclimation to the second skate. Subjects displayed a significant decrease in sagittal plane ankle ROM with the Mako skate; these effects were still present after further acclimation to the second skate. Subjects demonstrated increased maximum speed and decreased stride rate with the Mako skate; however, these effects faded slightly after further acclimation to the second skate.

CHAPTER 5: DISCUSSION

The purpose of this study was to investigate the effects of technique training and hockey skate design on treadmill skating performance and to more fully characterize kinematics during forward hockey skating. Subjects received technique training that promoted a wider lateral stroke, keeping the skate boot aligned in the direction of forward progression. It was hypothesized that this technique training would increase stride width with less foot outset at push-off and would also reduce anterior-posterior foot separation at push-off. This modified technique was also hypothesized to increase maximum speed and decrease stride rate. After five training sessions, subjects switched hockey skate types (TRAD to MAKO and vice versa) so that impact of hockey skate design could also be assessed. It was hypothesized that the increased sagittal plane flexibility of the Mako skate would increase ankle ROM and facilitate a more crouched posture thereby affecting knee, hip, pelvis and trunk ROM; the Mako skate was also hypothesized to increase speed, and decrease stride rate.

5.1 TECHNIQUE TRAINING EFFECTS

5.1.1 Kinematics

Initial post-training effects included increased stride width with the push-off foot more closely aligned with the direction of forward progression (i.e. reduced foot outset). The relative anterior-posterior foot separation also decreased post-training. These results are consistent with the goals of the technique instruction and confirm the related research hypotheses that specific technique training aimed at increasing stride width and reducing the anterior-posterior distance between the stance and push-off foot at foot-off would increase skating speed and efficiency (Table 5). Minimal additional effects in kinematic, and temporal and stride characteristics were observed following technique training with the second skate. The initial differences in stride width and foot position/outset at foot off remained and were not enhanced with additional technique training. This finding suggests that five sessions were sufficient for subjects to adjust to the alternative skating style, consistent with Lockwood and Frost [6] who noted habituation to a skating treadmill after four of six training sessions (4 minutes each for seven 10-year old hockey players). Future study that isolates skate treadmill acclimation from potential technique training effects might include an introductory period of treadmill skating prior to technique instruction and motion analysis. The current study indicates that five training sessions are sufficient; future studies might therefore reduce the number of training sessions from ten to five. Additional studies that more frequently assess training effects may further reduce the requisite number of sessions.

Despite the substantial coronal plane motion that occurs during ice-skating, stride width is not commonly reported in skating studies. The lack of stride width data may be attributed, at least in part, to motion analysis limitations. Kinematic investigation of hockey and speed-skating are frequently limited to sagittal plane analysis using one or two cameras for motion analysis [6, 9, 12, 33]. Two- (not three-) dimensional electro-goniometers on the lower extremity joints have also been used to investigate skating kinematics [5, 7].

Upjohn et al. reported values of mean stride width of high caliber adult hockey skaters (640 ± 90 mm, [11]), less than half that observed in the current study (1570 ± 170 mm). Pagé reported stride widths of approximately 1170 ± 170 mm during on-ice analysis of 14 youth and adult hockey skaters [23], still considerably less than those reported in the current study. The increased stride widths observed in the current study are likely due to the training technique that emphasized a lateral stroke on a level treadmill. The inclined treadmill used by Upjohn, Turcotte [11] likely encouraged a narrower stride. The reduced stride widths observed by Pagé may be attributed, at least in part, to the on-ice analysis, different motion analysis techniques and more common skating style.

In the current study, the differences in stride width and foot positioning post-training may be partially attributed to the increases in knee and ankle ROM in the sagittal plane, as well as ankle ROM in the coronal plane. The increases in sagittal plane ROM are due to increased ankle dorsiflexion and knee flexion during the glide period, or initial 50% of the skate cycle (Figure 11). The increased ankle motion in the coronal plane is due to increased inversion as the skater maintains blade contact with the treadmill surface during a wider stride. At foot-off, the ankle returns to a near neutral position as the subject rolls to the inside edge of the blade.

Throughout the skate cycle, differences in mean joint angle were observed post-training in all three planes for the ankle and knee joints, as well as for the hip joint in the transverse plane. Technique training resulted in position offsets in the coronal and transverse planes for the knee (-5.1° and 14.2°, respectively) and ankle (3.0°, and -10.30°, respectively). The subjects externally rotated their foot post-training. Despite this external foot rotation, these subjects demonstrated reduced foot outset angle (Figure 11) (Table 5), an apparent contradiction that may be attributed to the increased internal rotation of the shank relative to the thigh that thereby offset the externally rotated ankle (and hip). Together, these rotations resulted in a foot more closely aligned with the direction of travel, as intended by the alternative technique.

The technique instruction was expected to increase hip abduction and decrease thigh external rotation during push-off. However, no significant differences in hip angle were observed in the coronal plane; slight increases in hip abduction (not statistically significant) were observed during push-off only (Figure 11). In the transverse plane, external rotation of the hip or thigh actually increased during the recovery period, or latter 50% of the skate cycle. This counter-intuitive finding indicates that the increased stride width is not due to increased hip abduction and decreased external rotation of the hip, but may be attributed to increased lateral translation of the body center of mass in the global reference frame (i.e., instead of utilizing a larger ROM in the hip, the subjects translated their torso, upper extremities, and pelvis to obtain a wider stroke).

The only kinematic differences observed post-training in the second skate were significant decreases in spine angle, torso angle, and sacral height – differences that were also observed post-training with skate 1. Further analysis indicates that spine and torso angle were initially affected by the change in skate (e.g. establishing a new baseline); the decreases in spine angle, torso angle, and sacral height observed post-training, relative to this new baseline, returned to values observed post-training in skate 1. This result suggests that as subjects adjusted to the treadmill and subsequently to their new skates, they were able to crouch more as their comfort in the new skate increased. The significant differences in torso angle, spine angle, and sacral height were therefore not due to the technique instruction. Again, the lack of any additional kinematic differences in the session 6 versus 10 data suggests that subjects fully acclimated to the treadmill and had adopted the alternative technique by session 5.

Few prior studies have investigated the kinematics of hockey skating. As mentioned previously, Upjohn et al. [11] used motion analysis to characterize hip, knee and ankle motion of high (N=5) and low (N=5) caliber adult skaters on an inclined skating treadmill. While the morphology of the kinematic waveforms in the sagittal plane are comparable in both this and the current study, differences in the hip, knee, and ankle angles in the sagittal plane at foot strike are observed. At foot strike, Upjohn noted sagittal plane hip, knee and ankle angles of 46°, 49°, and 8°, respectively; the current study reported values of 70°, 75°, and 27°, respectively. The increased hip, knee and ankle flexion in the current study may be due to the level (versus inclined) treadmill orientation, skating technique, skate type, and/or subject age (teen versus adult). The knee flexion and dorsiflexion values measured in the current study with the level treadmill are consistent with those measured on-ice using goniometers (Stidwill et al. [21]; 86.9° and 18.6°). However, only the current study and Upjohn et al. fully characterized the three-dimensional kinematics of the lower extremities. Further studies are therefore needed to characterize three-dimensional joint angles and ROMs during forward on-ice skating.

5.1.2 Temporal and Stride Characteristics

Technique training also resulted in significant increases in maximum speed and decreased stride rate. Together, these findings support that this technique training may increase stroke efficiency and/or increase power per stroke. Further analysis is required to fully quantify the metrics responsible for these observed post-training differences.

The mean stride rates (0.60 to 0.70 strides/s at 4.2 to 6.3 m/s) recorded during the constant speed submaximal speed trials in this study are considerably less than that reported previously in treadmill skating studies. Stride rates of 0.77 to 1.09 strides/s at treadmill speeds ranging from 2.9 to 5.0 m/s have been reported for subjects ranging from 10 years to elite college and adult hockey players [6, 11, 20]. At first glance, the reduced stride rates observed in the current study might be attributed to the technique training that maximized stride width with a lateral stroke. However, lower stride rates were observed even during baseline treadmill skating during session 1, prior to technique training. As such, the reduced stride rates may be attributed to differences in treadmill orientation, which was level in the current study in contrast to more common inclined orientations (Upjohn et al., 2008). The inclined treadmill may have necessitated a more aggressive stroke, contributing to an increased stride rate relative to that observed in the current study. Level treadmills more closely approximate on-ice conditions; inclined treadmills are often used during training to increase strength and endurance.

The observed decreased stride rate and decreased spine angle, torso angle, and sacral height during the technique training sessions in skate 2 suggest these differences are due to acclimation to the alternative skate type, not further technique training effects.

The increased peak speed (5.1% relative to skate 1 post-training) observed at the end of skate 2 testing appears to be attributed to technique training, not the transition to skate 2. However, these increases in peak speed might also be influenced by increased subject strength after prolonged skating treadmill use since no kinematic mechanism appears responsible for the increase. However, such strength influences are likely minimal in the skate design analysis as skate order was randomly selected for subject groups. Future studies might quantify potential strength increases by measuring maximal lower limb joint torques at the beginning of each data collection session.

5.2 SKATE DESIGN EFFECTS

5.2.1 Temporal and Stride Characteristics

Initial skate design effects (sessions 5 and 6) indicated that subjects wearing the Mako skate increased their maximum speed and stride width while simultaneously decreasing stride rate, thereby supporting the posed research hypothesis that the Mako skate would impact skating performance. The increased speed and stride width, together with the decreased stride rate, may be indicative of a more efficient stride. Further study inclusive of kinetic measures, specifically push-off force, and metabolic cost are needed to confirm or refute this conjecture. As investigation of technique training effects indicated that training effects equilibrated within five sessions, changes in peak speed, stride width, and stride rate can be attributed solely to the skate design, with the Mako skate enhancing functional performance. The increased peak speed was sustained through skate 2 acclimation for subjects who started technique training in a traditional skate. For subjects who transitioned from the Mako to a traditional skate, the initial decreased peak speed partially faded after further acclimation to the traditional skate. The full effect of the Mako skate on peak speed for both subject groups was likely masked by ceiling effects, however, as several subjects were able to skate at the treadmill's maximum speed. Conducting maximum speed tests on-ice would facilitate more accurate assessment of speed effects with skate design, eliminating equipment limitations and any potential bias introduced by the treadmill operator.

5.2.2 Kinematics

One of the novel features of the Mako skate design is the flexible tendon guard. The increased sagittal plane flexibility of the skate boot was expected to *increase* ankle ROM in the sagittal plane. However, the Mako skate actually resulted in significantly *decreased* ankle ROM in the sagittal plane during submaximal speed trials; ankle ROM was approximately equivalent for the two skates during the maximum speed trials. As illustrated in Figure 13a and Figure 14a, ankle dorsiflexion at foot strike did not vary with skate design during the submaximal speed trials. The overall decrease in ankle ROM with the Mako skate during the submaximal speed trials may therefore be attributed to the decreased ankle dorsiflexion during glide, which offset the increased ankle dorsiflexion observed during the recovery phase.

The seemingly counter-intuitive reduced ankle ROM may indicate that the Mako skate promotes a more natural or preferred movement path of the ankle, a concept originally introduced by Nigg, Nurse [37]. The preferred movement path paradigm states that muscle activity will be reduced if an orthotic intervention (such as the skate boot) supports the preferred movement path of the joint. In other words, if the foot/ankle is unconstrained by an orthosis (or skate boot), the requisite muscle activity of that movement will be reduced when compared to a situation where the foot/ankle is constrained. In the constrained case, the foot/ankle achieves the same final position, but must travel a different path, with increased energy cost. Analysis of muscle activity while skating in boots of varying stiffness and height may be required to confirm this conjecture.

Another explanation for the unexpected decrease in sagittal plane ankle ROM is that while the Mako skate may provide additional plantar flexion flexibility, lacing and boot fit may still restrict dorsiflexion motion. Additionally, the increased ankle ROM observed with traditional skates may reflect greater ankle plantar flexion or “toe flick” during active push-off (50-60% skate cycle) to increase push-off force. The ankle plantar flexes through mid-recovery due to the momentum of the foot, contributing to reduced ankle dorsiflexion during recovery. Toe-flick, while fundamentally a sagittal plane motion, may also influence coronal plane kinematics. Skaters may be attempting to minimize potential skate blade drag along the skating surface, which would result in reduced coronal plane ankle/subtalar joint ROM. Incorporation of an instrumented skate blade or blade holder would facilitate kinetic analysis and future investigation of skate design effects on push-off force, and confirmation of the above conjecture.

Although full statistical analysis could not be performed on the maximal speed trial data due to maximum speed ceiling effects and the reduced subject population with full kinematic data, the ankle was less dorsiflexed during the glide period with the Mako skate during the maximum speed trials as well (Figure 13b and Figure 14b). In contrast to the submaximal speed trials, however, the ankle was also less dorsiflexed during the recovery phase with the Mako skate. As such, during the maximum speed trials, the sagittal plane ankle ROM was not reduced with the Mako skate, but was shifted approximately 5° (toward neutral) relative to the traditional skate. This again may indicate that the Mako skate promotes a preferred ankle joint movement pathway.

For post-acclimation analysis of skate effects (sessions 5 and 10), the only kinematic metric that exhibited significant difference with skate design was decreased ankle ROM in the sagittal plane during the submaximal trials. Marker dropout and ceiling effects, however, prevented kinematic analysis during the maximum speed trials. As such, while ankle ROM was reduced with the Mako skate at submaximal speeds, further studies that more fully characterize both passive and dynamic ankle kinematics are needed.

During the maximum speed trials knee flexion was reduced during the initial glide period with the Mako skate (Figure 15). While knee angle is approximately the same for both skates at initial push-off (50% skate cycle at contralateral foot strike), greater knee extension was observed during active push-off with the Mako skate. Increased knee extension has been correlated with increased power generation during skating, a kinematic mechanism that motivated the novel clap skate design [11, 14, 29, 32]. The observed increased knee extension with the Mako skate may also contribute to a kinematic mechanism for the observed increased maximum speed and decreased stride rate, and potential increased stroke efficiency.

Trunk posture was characterized by torso angle (sagittal plane forward lean) and spine angle (flexion/extension of trunk relative to pelvis, Figure 6). During the submaximal speed trials, subjects exhibited significantly increased spine angle with the Mako skate; torso angle, however, did not vary with skate design. This indicates that subjects significantly increased posterior pelvic tilt when wearing the Mako skate. Assuming constant knee flexion, increased posterior pelvic tilt stretches the hip flexor muscles and may contribute to a more efficient recovery phase. A posteriorly tilted pelvis may also facilitate increased hip flexion at foot strike, although no changes in hip ROM was observed in this study. Additional research is necessary to investigate the effects of a posteriorly tilted pelvis on skating kinematics.

To investigate whether the more crouched posture, reduced ankle motion, increased knee extension and posterior pelvic tilt with the Mako skate contributed to increased skate push-off force, the estimated motion of the body center of mass (COM) was reviewed. While body COM was not tracked directly, its motion might be approximated by that of the sacral marker. As per Newton's Second Law, the acceleration of the body COM is proportional to the applied force. Push-off force might therefore be approximated by the acceleration of the body (sacral marker) COM. Preliminary analysis of sacral marker acceleration during the maximum speed trials contrasting initial skate design effects (see Appendix B, Figure B-1) indicate slightly increased acceleration in both the lateraland anterior-posterior directions. In addition, peak COM was observed later in the skate cycle. These preliminary results indicate that the increased maximum speed attained in the Mako skate may be attributed to the increased acceleration of the body COM and push-off force, corresponding to the more favorable muscle mechanics associated with the observed postural changes (crouched posture, reduced ankle motion, increased knee extension and posterior pelvic tilt) and gravitational advantage with the Mako skate.

The *potential kinematic mechanism* contributing to the increased speed observed with the Mako skate is therefore increased acceleration of the body COM, which may be caused by the reduced ankle dorsiflexion throughout the skate cycle, increased knee extension during active push-off, movement that is facilitated by the more flexible tendon guard and tighter, more intimately fitted skate boot Further investigation is needed to investigate these preliminary findings and potential mechanisms.

Although knee and ankle ROM and foot positioning at foot-off varied with technique training, no such differences were observed during analysis of initial skate design effects (session 5 versus 6 data) during submaximal speed trials. Comparison of skate 1 baseline and post-training data indicated that relative foot position and foot angle at foot-off decreased with technique training. Subjects also displayed increased knee flexion and ankle dorsiflexion at foot strike after skate treadmill/technique training. These differences were not observed during analysis of either initial or post-acclimation skate effects at submaximal speed, suggesting again that *training effects (and treadmill acclimation) equilibrated over the initial five training sessions*.

5.4 LIMITATIONS

5.4.1 Equipment

This study was restricted to the investigation of kinematic effects of technique training and skate design during treadmill skating. Prior studies contrasting the kinematics of forward skating on-ice versus on a skating treadmill or synthetic ice surface indicate that there are no major kinematic differences between the test conditions [4, 5, 20]. However, a skating treadmill permits analysis of forward skating kinematics only. Turning, transitions from forward to backward skating, and skating agility are essential skills for overall hockey skating performance [2]; the kinematics of these skills can only be assessed on-ice.

Several subjects were able to skate at the maximum treadmill speed, introducing a ceiling effect and preventing analysis of technique training and/or skate design on subjects' peak speeds. Additionally, the treadmill belt width was approximately 240 cm. Subjects with the widest strides (160-190 cm) may have modulated their stride to this constraint. While neither of these hardware limitations prevented identification of statistically significant differences, the magnitude of such differences may have been reduced. In addition, the potential significance of other potential differences may have been masked by these equipment limitations. Full assessment of the effects of technique training and skate design on hockey performance requires on-ice testing.

The accuracy of the three-dimensional kinematic data is affected by camera field of view, the kinematic model, marker motion artifacts due to skin/clothing movement, and foot segment marker placement (metatarsal head, lateral malleolus and heel) on the skate boot. The Vicon PIG model used in this study was developed for walking and running analyses for which coronal and transverse plane movements are minimal. Cardan angle calculation used to determine three-dimensional joint angle first defines the rotation in the sagittal plane followed by the coronal and transverse planes, with each successive angle calculation dependent on the previous. As such, the accuracy of sagittal plane joint angles actually exceeds that for the coronal and transverse planes (see Appendix B, Figure C-1). In this study, sagittal plane kinematic analyses were the primary basis for discussion and identification of potential kinematic mechanisms. However, coronal plane movement is also important in hockey. As such, a new full body kinematic model may need to be developed to fully assess kinematic effects on hockey skating performance. The placement of the foot and ankle markers on the skate boot likely underestimated ankle motion in both skates [5, 22, 38]. However, there is no way to mitigate the motion artifacts associated with the skate boot without compromising the integrity of the boot structure.

5.4.2 Subject Recruitment

The recruited subjects were aged 12-16 years and had at least 7 years of hockey experience. The musculoskeletal development of individuals in this age span may vary greatly. Skaters in this age range and skill level, however, were deliberately selected as these individuals may receive greater benefit from technique training and may be more open to alternative skating technique. As data analyses were conducted via paired t-tests, the effects of variability in body maturity and skill level were minimized. Study results, however, cannot be extrapolated to other ages and/or skill levels.

Subject recruitment and retention also resulted in unbalanced comparative groups. Subjects were placed in the MAKO group if they already owned Mako skates; all other subjects were placed in the TRAD group until the target population of 10 subjects per group was recruited. . Due to start of the school year, subject recruitment was terminated prior to full recruitment of the MAKO group. This group imbalance was further hindered by the greater subject withdrawal from the MAKO group. While the initial groups sizes were 10 and seven for the TRAD and MAKO groups, respectively, the final group sizes were nine and five. Skate design analysis was likely impacted by the unbalanced groups, with the TRAD group more heavily weighted than the MAKO group. Since the TRAD group was switching to the unfamiliar Mako skate, however, the impact of the unbalanced groups likely minimized the overall performance increases in the Mako skate, perhaps masking potential differences in skate design. Ultimately, a more balanced study population design is desirable for future studies.

5.4.3 Investigator Bias

The goal of this study was to assess the effects of technique training and skate design on skating performance as subjects progressed through a training program. As such, the technique coach was intimately involved in the training sessions during which motion analysis was conducted. The maximum speed trials were particularly susceptible to investigator bias, as the coach controlled the treadmill speed and initial values were based on subject performance during prior trials and sessions. While intentional bias is not suspected, unintentional bias may have occurred. It is not possible to blind the treadmill operator to either treadmill speed or its effect on subject skating performance. However, future studies might be based on more systematic selection of initial treadmill speed and adjustment or on-ice speed trials to minimize introduction of potential bias in peak speed assessment.

5.5 FUTURE STUDIES

Study results were affected by incorporation of a skating treadmill. Kinematic assessment was limited to forward skating only and maximum speed was constrained to 8.9 m/s. Advances in wireless technology may overcome challenges of on-ice motion analysis and facilitate kinematic assessments of multiple skating skills.

The results of this study suggest that technique training and use of the Mako skate result in potentially more efficient strides. To further investigate stroke efficiency, future studies might include kinetic evaluation, particularly with respect to measurement of skate push-off force (over body COM acceleration) and metabolic cost. Kinetic assessment might incorporate insole force sensors [4, 39] or an instrumented skate blade, during both treadmill and on-ice skating tasks.

This study also indicated that skating performance is affected by skate boot design. Future studies might evaluate skate boot fit and passive ankle ROM within the skate boot. These future studies might also decouple treadmill acclimation from technique training, incorporating 3-5 treadmill skating sessions purely for acclimation prior to initiating technique training.

To date, investigation of ice and hockey skating has been limited, particularly with respect to kinematic and kinetic characterization. This study helped define and characterize temporal, stride and kinematic metrics of skating performance, and identified potential kinematic mechanisms contributing to performance changes. Future studies with more refined hypotheses and larger, balanced sample sizes are required to more fully investigate the effects of technique training and skate design features on skating performance.

CHAPTER 6: CONCLUSIONS

The purpose of this study was to investigate the effects of technique training and hockey skate design on performance and to more fully characterize the kinematics of forward hockey skating. Hockey players typically employ a narrow skating stride with large anterior-posterior separation at foot off between the stroke and push-off. In contrast, speed skaters utilize a wider stride with reduced anterior-posterior foot separation. Compared to a traditional hockey skate design, the Easton Mako skate incorporates a flexible tendon guard allowing more passive ankle flexion and extension and a heat-moldable skate boot allowing for enhanced conformity to the underlying anatomy. Both technique training based on speed-skating style and the increased flexibility and conformation of the Mako skate were speculated to improve skating performance. The specific research questions addressed in this study were: 1) Can skate treadmill technique training improve skating performance in terms of speed and efficiency? and 2) Does skate boot design affect skating performance in terms of posture, speed and efficiency? The related research hypotheses investigated in this study were that: 1) technique training incorporating a lateral stroke increases skating speed and skate stroke efficiency and 2) a skate boot with increased anterior-posterior flexibility accommodates a more crouched, ergonomic posture that results in increased skating speed and efficiency.

Fourteen male subjects, aged 12-16 years, with no recent skate treadmill experience completed ten training sessions on a skating treadmill while receiving technique instruction that emphasized a more lateral push-off stroke with reduced anterior-posterior foot separation at foot off. Subjects were placed into one of two experimental groups defining their initial skate type: traditional or Mako. Subjects performed the first five training sessions in their initially assigned skate; after five sessions, skate type was switched.

Kinematic data were acquired during submaximal constant speed trials and maximum speed tests, at the first (baseline, skate 1), fifth (post-training, skate 1), sixth (baseline, skate 2), and tenth (post-acclimation, skate 2) training sessions. Treadmill training effects were investigated contrasting data from sessions 1 and 5, and sessions 6 and 10. Skate design effects were investigated contrasting data from sessions 5 and 6, and sessions 5 and 10. Significance was assessed using paired t-tests.

Significant initial training effects included increased stride width and decreased anterior-posterior foot separation, and decreased relative push-off foot angle in the transverse plane as intended by the specific technique. Other effects included decreased stride rate at a constant speed, and increased maximum speed. The hypothesis that technique training incorporating a lateral stroke increases skating speed and skate stroke efficiency was therefore supported. Initial training effects were maintained through the latter training sessions suggesting five sessions were sufficient to acclimate to the skating treadmill and adopt the new skating technique. Significant skate design effects included decreased sagittal ankle ROM, decreased stride rate at constant speed, increased stride width, and increased maximum speed with the Mako skate. The decreased sagittal plane ankle ROM may be indicative of a more natural ankle movement. The increased maximum speed, in concert with decreased stride rate, suggest a potentially more efficient stride with the Mako skate. The research hypothesis that a skate boot with increased anterior-posterior flexibility accommodates a more crouched, ergonomic posture that yields increased skating speed and efficiency was partially supported. The potential mechanism for the increased maximum speed and reduced stride rate in the Mako skate increased acceleration of the body COM, which may be caused by the reduced ankle dorsiflexion throughout the skate cycle, increased knee extension during active push-off, movement that is facilitated by the more flexible tendon guard and tighter, more intimately fitted skate boot

The current investigation served as a pilot study and successfully identified temporal, stride, and kinematic metrics of interest. Future work involving on-ice analysis and skate push-off force are recommended to further investigate the preliminary findings of this study.

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APPENDIX A: STATISTICAL ANALYSIS

Table A - 1. Statistical analyses of technique training metrics.

	Initial Effects (Session 1 vs. Session 5)					Post-switch Effects (Session 6 vs. Session 10)				
	p	Effect Size	Normality	Power (*a priori*)	Power (*post hoc*)	p	Effect Size	Normality	Power (*a priori*)	Power (*post hoc*)
Temporal and Stride Metrics										
Maximum Speed (m/s)#,**,♮♮♮	**0.017**	**0.71**	**0.135**	**12**	**0.81**	**0.006**	**0.80**	**0.747**	**10**	**0.88**
+Stride Rate (1/s)***, ♮♮	**0.005**	**0.91**	**0.984**	**9**	**0.94**	**0.028**	**1.17**	**0.088**	**16**	**0.99**
Glide Duration (% cycle)	0.965	0.00	0.329	>1000	-	0.679	0.10	0.810	485	0.10
Single Support (% cycle)	0.916	0.02	0.537	620	0.06	0.492	0.18	0.864	174	0.16
Stride Width (cm)***	**0.007**	**2.35**	**0.627**	**11**	**1.00**	0.814	0.07	0.024	>1000	0.08
Lower Extremity ROM										
Hip ROM Sagittal (°)	0.198	0.26	0.294	91	0.24	0.393	0.23	0.515	112	0.20
Hip ROM Coronal (°)	0.270	0.35	0.155	52	0.34	0.234	0.32	0.465	58	0.31
Hip ROM Transverse (°)	0.772	0.11	0.798	515	0.10	0.947	0.01	0.273	>1000	0.05
Knee ROM Sagittal (°)**	**0.022**	**0.70**	**0.285**	**15**	**0.80**	0.365	0.26	0.313	100	0.24
Knee ROM Coronal (°)	0.961	0.02	0.800	>1000	0.06	0.439	0.24	0.748	138	0.21
Knee ROM Transverse (°)	0.934	0.02	0.062	>1000	0.06	0.862	0.03	0.357	>1000	0.06
Ankle ROM Sagittal (°)**	**0.016**	**0.75**	**0.886**	**13**	**0.84**	0.273	0.29	0.806	68	0.27
Ankle ROM Coronal (°)**	**0.027**	**0.62**	**0.935**	**18**	**0.71**	0.120	0.44	0.118	33	0.47
Ankle ROM Transverse (°)	0.431	0.25	0.716	101	0.22	0.102	0.47	0.342	30	0.51

Mean Joint Angle										
Hip Sagittal (°)	0.362	0.10	0.252	612	0.10	0.531	0.17	0.129	211	0.15
Hip Coronal (°)♮♮♮	0.570	0.05	0.294	>1000	0.07	**0.000**	**1.42**	**0.101**	**5**	**0.99**
Hip Transverse (°)* **	**0.084**	**0.37**	**0.105**	**46**	**0.37**	0.186	0.38	0.314	46	0.38
Knee Sagittal (°) **	**0.027**	**0.59**	**0.022**	**20**	**0.67**	0.306	0.28	0.126	78	0.26
Knee Coronal (°) **	**0.077**	**0.39**	**0.323**	**42**	**0.40**	0.145	0.42	0.026	38	0.44
Knee Transverse (°)*,♮♮**	**0.001**	**0.86**	**0.169**	**10**	**0.92**	**0.027**	**0.67**	**0.847**	**16**	**0.77**
Ankle Sagittal (°) **	**0.011**	**0.60**	**0.925**	**19**	**0.68**	0.984	0.00	0.011	>1000	-
Ankle Coronal (°)* **	**0.001**	**0.81**	**0.898**	**11**	**0.89**	0.123	0.28	0.123	34	0.26
Ankle Transverse (°)*,♮♮**	**0.002**	**0.76**	**0.446**	**13**	**0.85**	**0.082**	**0.51**	**0.883**	**26**	**0.56**
Sagittal Position at Foot-Strike										
Sacral Height (relative to standing sacral height) ♮♮♮	0.553	0.01	0.484	>1000	0.05	**0.002**	**1.00**	**.399**	**11**	**0.97**
Hip Angle (°)	0.656	0.14	0.823	340	0.13	0.467	0.20	0.090	151	0.17
Knee Angle (°) **	**0.060**	**0.50**	**0.503**	**27**	**0.55**	0.408	0.23	0.028	123	0.20
Ankle Angle (°)	0.431	0.61	0.506	19	0.70	0.387	0.23	0.913	120	0.20
Torso Angle (°)♮♮♮	0.209	0.38	0.521	44	0.38	**0.009**	**0.82**	**0.132**	**10**	**0.90**
Spine Angle (°)♮♮♮	0.328	0.30	0.942	72	0.28	**0.006**	**0.87**	**0.631**	**11**	**0.92**
Foot Position at Foot-Off										
Foot Position (cm)*	**0.066**	**0.46**	**0.053**	**31**	**0.49**	0.344	0.26	0.352	135	0.24
Foot Angle (°)*	**0.094**	**0.40**	**0.494**	**40**	**0.41**	0.436	0.21	0.613	92	0.18

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$ *in session 1 vs. session 5 comparison*

♮♮♮ $p < 0.01$, ♮♮ $p < 0.05$, ♮ $p < 0.10$ *in session 6 vs. session 10 comparison*

Table A - 2. Statistical analyses of skate design metrics.

	Initial Effects (Session 5 and 6 TRAD v MAKO)					**Post-Acclimation (Session 5 and 10 TRAD v MAKO)**				
	p	Effect Size	Normality	Power (*a priori*)	Power (*post-hoc*)	p	Effect Size	Normality	Power (*a priori*)	Power (*post-hoc*)
Temporal and Stride Metrics										
Maximum Speed (m/s)*,♮♮♮**	**0.001**	**1.67**	**0.332**	**4**	**0.99**	**0.002**	1.60	**0.382**	**8**	**0.99**
+**Stride Rate (1/s)****	**0.031**	**0.67**	**0.760**	**16**	**0.77**	0.872	0.20	0.019	>1000	0.17
Glide Duration (% cycle)	0.681	0.17	0.222	224	0.14	0.658	0.20	0.259	410	0.17
Single Support (% cycle)	0.191	0.10	0.285	620	0.10	0.603	0.26	0.364	304	0.23
Stride Width (cm)*	**0.082**	**0.40**	**0.166**	**41**	**0.41**	0.298	0.29	0.049	76	0.27
Lower Extremity ROM										
Hip Sagittal (°)	0.798	0.07	0.071	1179	0.08	0.452	0.18	0.341	145	0.16
Hip Coronal (°)	0.256	0.17	0.479	224	0.14	0.594	0.24	0.012	291	0.21
Hip Transverse (°)	0.312	0.30	0.018	72	0.28	0.389	0.24	0.323	111	0.21
Knee Sagittal (°)	0.647	0.13	0.030	381	0.12	0.176	0.38	0.857	44	0.38
Knee Coronal (°)	0.637	0.14	0.355	330	0.13	0.936	0.39	0.287	>1000	0.40
Knee Transverse (°)	0.905	0.02	0.144	>1000	0.06	0.177	0.02	0.718	44	0.06
Ankle Sagittal (°),♮♮**	**0.012**	**0.69**	**0.821**	**15**	**0.79**	**0.036**	**0.63**	**0.232**	**18**	**0.72**
Ankle Coronal (°)*	**0.071**	**0.44**	**0.532**	**33**	**0.47**	0.125	0.44	0.762	34	0.47
Ankle Transverse (°)	0.560	0.12	0.047	423	0.11	0.560	0.16	0.118	242	0.14
Mean Joint Angle										
Hip Sagittal (°)	0.455	0.20	0.488	151	0.17	0.950	0.02	0.998	>1000	0.06
Hip Coronal (°)	0.156	0.43	0.589	35	0.45	0.976	0.00	0.334	>1000	**-**

Hip Transverse (°)	0.441	0.22	0.041	136	0.19	0.694	0.11	0.843	530	0.10
Knee Sagittal (°)♮	0.368	0.24	0.954	108	0.21	**0.057**	**0.58**	**0.772**	**22**	**0.66**
Knee Coronal (°)	0.538	0.17	0.053	206	0.15	0.992	0.00	0.779	>1000	-
Knee Transverse (°)	0.121	0.44	0.539	34	0.47	0.158	0.40	0.476	40	0.41
Ankle Sagittal (°)	0.744	0.09	0.460	697	0.09	0.341	0.26	0.816	91	0.24
Ankle Coronal (°)*,♮	**0.083**	**0.50**	**0.804**	**27**	**0.55**	**0.100**	**0.48**	**0.831**	**29**	**0.52**
Ankle Transverse (°)*	**0.080**	**0.50**	**0.833**	**26**	**0.55**	0.112	0.45	0.960	32	0.48
Sagittal Position at Foot-Strike										
Sacral Height (relative to standing sacral height) ♮♮♮	0.405	0.03	0.689	>1000	0.06	0.711	0.05	0.375	>1000	0.07
Hip Angle (°)	0.507	0.18	0.368	196	0.15	0.869	0.05	0.969	>1000	0.07
Knee Angle (°)	0.623	0.12	0.309	418	0.11	0.263	0.33	0.100	58	0.32
Ankle Angle (°)	0.706	0.11	0.548	560	0.10	0.374	0.23	0.104	>1000	0.20
Torso Angle (°)	0.174	0.26	0.855	92	0.23	0.778	0.08	0.108	>1000	0.09
Spine Angle (°)*	**0.094**	**0.37**	**0.710**	**47**	**0.37**	0.841	0.05	0.823	>1000	0.07
Foot Position at Foot-Off										
Foot Position (cm)	0.294	0.15	0.649	267	0.13	0.714	0.11	0.908	1435	0.10
Foot Angle (°)	0.156	0.28	0.243	82	0.26	0.810	0.06	0.626	622	0.08

*** *p < 0.01,* ** *p < 0.05,* * *p < 0.10 in session 5 and 6 comparison of TRAD vs. MAKO*

♮♮♮ *p < 0.01,* ♮♮ *p < 0.05,* ♮ *p < 0.10 in session 5 and 10 comparison of TRAD vs. MAKO*

APPENDIX B: APPROXIMATE CENTER OF MASS ANALYSIS

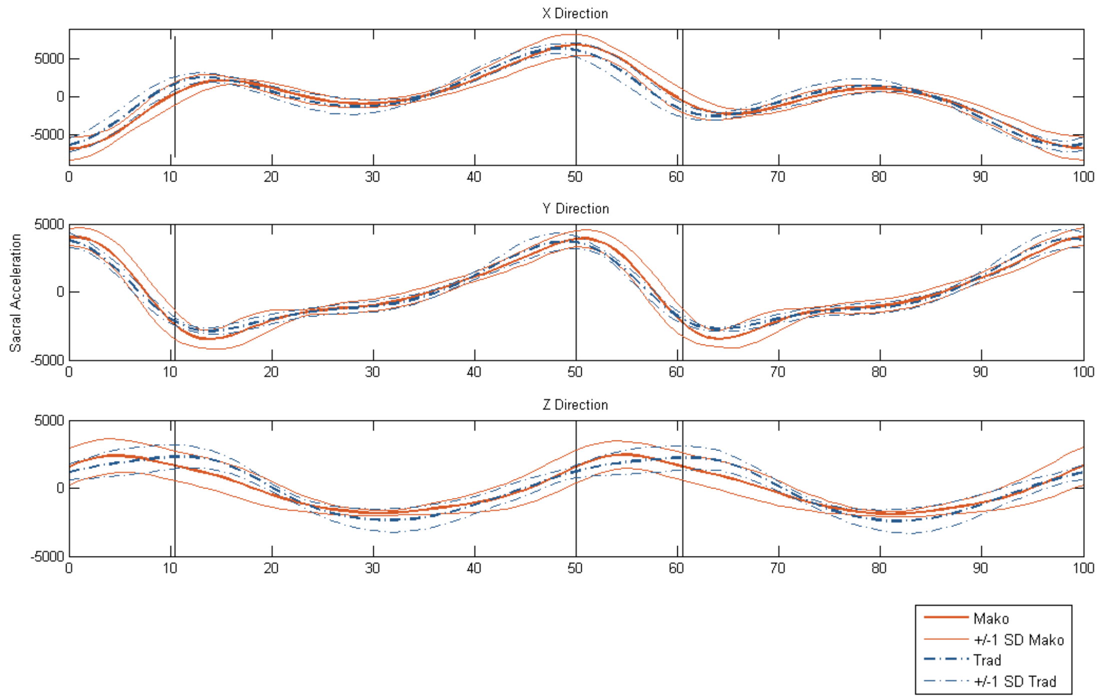

Figure B - 1. Initial skate design effects during maximum speed trials (sessions 5 and 6, N=6). Mean sacral marker acceleration (mm/s^2), approximating the body COM acceleration and push-off force in the global reference frame defined in Figure 5.

APPENDIX C: ANGLE ERROR ANALYSIS

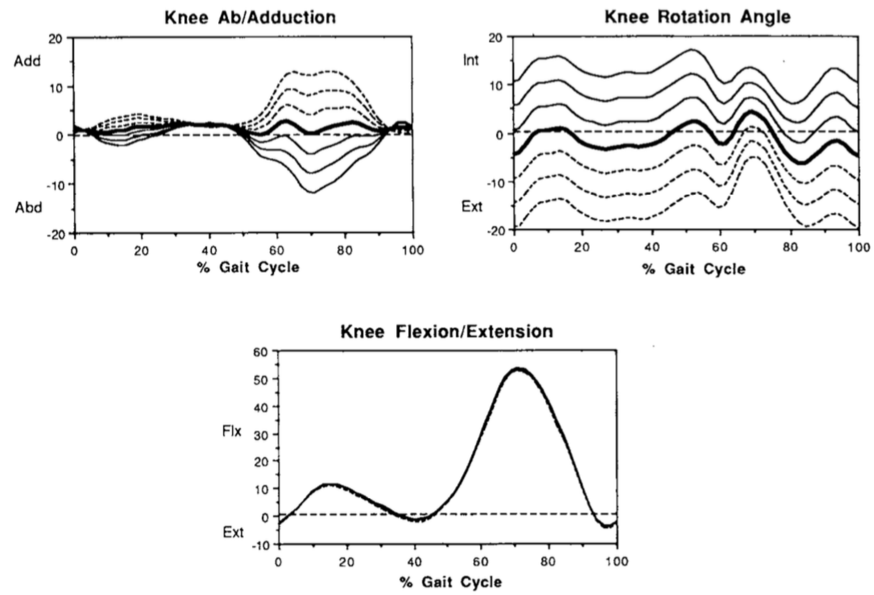

Figure C-1. Potential error in knee joint angle introduced when the flexion/extension axis of the joint is not defined correctly due to a misplaced marker. Angles errors are amplified in the frontal and transverse planes due to Cardan angle calculation sequencing. Bold line indicates correct marker placement (no error in knee axis position); other lines indicate positive (solid) or negative (dotted) errors in knee axis location in increments of 5°.