On-ice Acceleration as a Function of the Wingate Anaerobic Test and a Biomechanical Assessment of Skating Technique, in Elite Ice Hockey Players

by:

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Abstract

Success in ice hockey depends on an individual's ability to accelerate from a standing start or change direction and continue skating quickly and efficiently. Previous research to determine those factors which had the greatest contribution to on-ice acceleration was limited to two-dimensional biomechanical analyses of skating technique, without regard for the influence of physiological measures. The purpose of the present study was therefore to predict on-ice acceleration using peak anaerobic power from a Wingate test and kinematic variables from a three dimensional analysis of the biomechanics of skating technique. A sub-purpose of the present study was to examine the variability of skating technique at the elite level. The participants in this research study were thirty-seven ice hockey players from the Florida Panthers and Los Angeles Kings of the National Hockey League participating in the 1999 Prospects Camp in Thunder Bay, Ontario. The players completed a thirty second, maximal intensity Wingate anaerobic cycle ergometer test against a resistance of 0.095 $kg \cdot kg$ $bodyweight^{-1}$. Peak anaerobic power was calculated and recorded as the highest anaerobic power value (number of flywheel revolutions) produced during any of the five-second intervals. One week following the Wingate anaerobic test, the players performed two maximal, on-ice accelerations over a distance of twenty meters, while being taped by two, Panasonic™ CL-350 digital cameras mounted on Peak Performance™ pan/tilt heads. The Peak Performance™ 3D Video Analysis System and a 23-point spatial model were used to extract the raw coordinates for the fastest of the two trials for each player, as measured by a photoelectric timer. The system was then used to smooth the raw data from both camera views and to combine the smoothed data to produce a three-dimensional image. Center of mass and kinematic variables of interest were measured at push-off and touchdown for the first five strides. Time, velocity and average acceleration were measured

1.52 m, 3.03 m, 4.54 m, and 6.06 m from the first push-off. Descriptive statistics for all kinematic data were performed using SPSS™, Version 9.0. Exploratory principal components factor analyses (PCA) were used to a) filter the set of predictor variables by eliminating confounding kinematic variables from further analyses, and b) identify the underlying relationships between groups of kinematic variables which represent important characteristics of ice hockey skating. Performance measures for strides loading in series within variable sets identified by the PCA were transposed into a single composite score using a log-log transformation of the power function. The factor analyses and log-log transformations were performed using SAS™, Version 6.12. Multiple regression analysis using a backward stepwise approach was used to determine the set of variables that best predict on-ice acceleration (time taken to skate 6.06 m). The variability in skating technique used by the players was examined using estimates of skewness and kurtosis for the variables identified by the PCA and predictors of time to skate six meters. The results of the PCA in this study highlighted three latent variables that described several important characteristics of skating technique that influence skating performance in ice hockey. The factor loadings on each latent variable indicated that in order to optimize skating performance, players should attempt to maximize their push-off during the first stride, prepare for propulsion with knees fully flexed at touchdown and most importantly maintain an efficient body position throughout acceleration to maximize propulsion. Regression analysis revealed that the time taken to skate six meters is best predicted by player height, stride length, propulsive time, peak anaerobic power, hip and knee angle at push-off on the first stride, hip abduction angle at push-off, and toe-to-center of mass distance at touchdown on the third stride. The homogeneity of variance in the kinematic measures that predicted skating performance indicates that little variability exists in the skating technique used by ice hockey players at the elite level. Therefore, the results of the present study have shown that on-ice accleration can be predicted using peak anaerobic power from a Wingate test and kinematic variables from a three dimensional analysis of the biomechanics of skating technique.

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Acknowledgements

"DESTINY IS NOT A MATTER OF CHANCE,
IT IS A MATTER OF **CHOICE.**"

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Introduction

The game of ice hockey has been referred to by sport scientists as the fastest sport in the world of professional athletics (Cox, Miles, Verde & Rhodes, 1995; Mascaro, Seaver & Swanson, 1992). For years, owners, coaches and players of the game of ice hockey have sought the support and expertise of sports scientists in an attempt to maximize athletic performance.

Analysis of time-motion characteristics in professional and college ice hockey have shown that the typical shift is between 45 and 85 seconds in length, with 2-3 bouts of intense skating interspersed with short periods of recovery (Bracko, Fellingham, Hall, Fisher & Cryer, 1998; Cox et al., 1995). Whether it be "hustling" back on defense, avoiding or initiating important checks, capitalizing on breakaway opportunities or consistently winning the race to the puck, the ability to skate quickly and efficiently is fundamental to each shift in the game of ice hockey. However, frequent changes in direction are inevitable since the dimensions of the ice surface limit the maintenance of maximal skating velocities (Marino, 1983). Therefore, although skating speed and efficiency are important in ice hockey, the ability to accelerate rapidly from a standing start or from a minimal velocity to a maximal velocity in a short period of time is essential (Marino, 1983).

Successful hockey players are generally assumed to be technically skilled skaters, however, there is a lack of scientific literature defining "good" skating technique (Twist & Rhodes, 1993). Further, sport scientists have indicated that although skating technique is important in ice hockey, biomechanical studies examining this characteristic are scarce (Cox et al., 1995; Pagé, 1976). Nevertheless, researchers have highlighted numerous kinematic variables in an attempt to predict skating speed or skating performance in ice hockey.

The motion of each leg during skating can be divided into three phases: glide, push-off, and recovery (Allinger & Van den Bogert, 1997). The glide phase occurs when the body's weight is supported over one leg, which remains nearly constant in length (Allinger & Van den Bogert, 1997). The push-off phase commences with the initiation of leg extension and ends when the leg nears full extension and the skate blade loses contact with the ice surface (Allinger & Van den Bogert, 1997; Marino, 1983; Marino & Weese, 1979). Finally, the recovery phase begins at the completion of push-off and finishes when the skate contacts the ice (touchdown) in its starting position, completing the skating cycle (Allinger & Van den Bogert, 1997; Marino, 1983; Marino & Weese, 1979). Examining the combined action of the legs, there are alternating periods of single support (one skate in contact with ice) and double support (both skates in contact with the ice) (Marino, 1979). The single support period is often a glide phase and propulsion or push-off occurs during the double support period (Marino, 1979). However, Marino (1979) has suggested that during acceleration, propulsion can occur during the double support and single support periods. In an attempt to understand skating technique, researchers have focused their biomechanical analyses on two specific events during the skating stride, push-off and touchdown, which together reflect the three phases of skating (Marino, 1983; Marino, 1979; Marino & Dillman, 1976; Pagé, 1976).

Marino & Dillman (1976) performed multiple linear regression and forward selection stepwise regression analyses using selected mechanical variables to determine the predictability of average acceleration over twenty feet (6.06 m), instantaneous skating velocity at twenty feet (6.06 m) and time to skate twenty feet (6.06 m). Using Stein's cross validation estimation, these researchers found that regression models using mechanical variables from each of the first three individual strides were not sufficient to account for the variance in acceleration (Marino &

Dillman, 1976). However, multiple regression using means of the mechanical variables over the first three strides was found to be more accurate in predicting acceleration (Marino & Dillman, 1976). Forward selection stepwise analysis was used to find the best set of predictors which related acceleration, velocity and skate time to technique (Marino & Dillman, 1976). The results of this stepwise analysis produced the following regression equation for average acceleration (Marino & Dillman, 1976):

$$\hat{Y} = -2.466X_1 - 0.062X_2 + 0.012X_3 + 0.443X_4 - 0.007X_5 + 2.070X_6 + 2.938$$

where, X_1 = toe to hip distance at touchdown

X_2 = angle of takeoff

X_3 = weight

X_4 = stride rate

X_5 = forward lean at touchdown

X_6 = leg length

Similarly for instantaneous velocity, toe to hip distance at touchdown, angle of takeoff, weight and stride length were found to be the best set of predictors. However, the multiple correlation coefficient of $R = .58$ (S.E.E. = .747) indicated a low predictability of velocity using this model (Marino & Dillman, 1976). Finally, Marino & Dillman (1976) reported the following regression equation for the time taken to skate twenty feet (6.06 m):

$$\hat{Y} = 0.004X_1 + 0.013X_2 - 0.143X_3 - 0.399X_4 + 2.31$$

where, X_1 = forward lean at touchdown

X_2 = angle of takeoff

X_3 = stride rate

X_4 = height

The results of Marino & Dillman's (1976) research provided insight into important mechanical variables associated with ice hockey skating as well as the use of statistical modeling to predict performance.

In 1976, Pagé conducted a biomechanical analysis of skating technique for players of various ages and abilities in an attempt to discover factors that accounted for observed differences in forward skating speed. Pairwise correlation analyses revealed significant ($p<0.05$) positive relationships between skating speed and five kinematic measures, width of the left and right strides, length of the left and right strides, and the range of knee extension (Pagé, 1976). Moreover, Pagé (1976) found significant negative relationships between skating speed and five different kinematic measures, angle of knee flexion, total recovery time of the skated blade, mid-recovery time of the skate blade, angle of the trunk, and time of knee extension. Following a multiple stepwise discriminant analysis, Pagé (1976) observed that faster skaters maintained a greater degree of forward lean of the upper body, smaller angle of knee flexion prior to the initiation of push-off, and a greater angle of abduction of the leg at push-off than slower skaters. Pagé (1976) concluded that these body positions enabled the faster skaters to maximize their propulsive force in a downward, sideways, and backwards direction, whereas the body positions of the slower skaters limited the amount of propulsive force that could be created in the sideways and backwards directions.

Using the same data set as Marino & Dillman (1976), Marino (1983) created a Pearson product moment correlation matrix between mechanical variables and skating criterion variables. Using a significance level of $p<0.01$, Marino (1983) found significant relationships between three variables (single support time, stride rate, and toe to hip distance at touchdown) and acceleration. Single support time (SST) showed a significant negative relationship ($r = -.37$)

with acceleration, while stride rate (SR) showed a significant positive relationship (r = .36) with acceleration. The placement of the recovery leg upon touchdown (THD) was found to have a significantly negative relationship (r = -.41) with acceleration. Marino (1983) also determined that the propulsive angle of the skate (PA) and lean angle at touchdown (LTD) showed indirect relationships with acceleration. Although PA was not significantly related to acceleration, it showed a significant relationship (r = .39) with SR. This suggested that a rapid acceleration was related to a rapid stride rate, which in turn was related to a large propulsive angle during push-off. Similarly, LTD was significantly related (r = .48) to skate time which showed a significant relationship (r = -.48) to acceleration. Thus, Marino (1983) proposed that LTD was an indication of the optimization of propulsive forces in magnitude and direction. Confirming the earlier findings of Marino & Dillman (1976) and Pagé (1976), Marino (1983) showed that acceleration is associated with a high stride rate, low angle of forward lean at touchdown, short single support period and placement of the recovery leg directly beneath the body.

Although these investigations provided insight into important mechanical variables that can be used to predict acceleration, the robustness of the results is limited in three ways. First, these studies are limited by the use of two-dimensional, rather than three-dimensional analyses of skating technique. Perspective error restricts two-dimensional videography to relatively small field widths and linear motion where movements occur only in the X-Y coordinate system. Three-dimensional analyses (using pan & tilt), however, allow for the analysis of movements in larger field widths with movements in all three planes of motion: saggital, frontal, and transverse. Secondly, collapsing kinematic measures for the initial strides into a mean score, as done by Marino & Dillman (1976) and used again by Marino (1983), may obscure unique characteristics of the progression in the skating stride over time. The technique used by players in their first stride may differ significantly from that of the second and third, therefore, it is important that biomechanical analyses examine each skating stride individually. Finally, biomechanical research on skating technique in ice hockey has neglected to investigate the contribution of physiological measures, such as anaerobic power and capacity, on skating performance.

The physiological characteristics of ice hockey players, especially at the elite level, are tested regularly by coaches and trainers as a means of quantifying physical fitness (Cox et al., 1995). Of greatest interest to the coach, trainer and athlete are the results of tests of anaerobic and aerobic fitness, as these results are most indicative of athletic and performance potential. The difficulty, however, lies in the development of standardized testing protocols that replicate the physiological demands placed on the players in game situations. Moreover, no international standards have been developed for the physiological assessment of elite ice hockey players (Cox et al., 1995).

Vandewalle, Peres & Monod (1987) and Cox et al. (1995) reported that the most widely used off-ice test of anaerobic power and capacity is the Wingate anaerobic cycle ergometer test (WAT), developed by Ayalon, Inbar & Bar-Or (1974). Although a more precise measure of an athlete's potential for anaerobic power and capacity could be derived through the analysis of muscle tissue following a biopsy, this procedure is invasive, expensive and time-consuming (Scott, Roby, Lohman & Bunt, 1991). The WAT protocol on the other hand is non-invasive, simple to administer, short in length, relatively inexpensive and provides instantaneous feedback of results. Therefore, coaches and sport scientists have used the WAT to quantify anaerobic fitness in ice hockey players. In an attempt to replicate the physiological demands placed on the players in game situations in ice hockey, researchers have manipulated the length, intensity and the amount of resistance used in the WAT. However, criticism by researchers regarding the external validity of the WAT, has prompted the development of on-ice tests of anaerobic power and capacity, such as the Repeat Sprint Skate (RSS) (Reed, Hansen, Cotton, Gauthier, Jette, Thoden & Wenger, 1979). The major criticism of using the WAT as a test of anaerobic fitness in ice hockey is the difference in the motor pattern between cycling and skating (Watson & Sargeant, 1986). Although on-ice tests of anaerobic power and capacity incorporate skating motor patterns, performance on these tests is not based solely on physiological fitness but also on skating technique. Therefore, it is impossible to accurately measure anaerobic power and capacity using an on-ice test without factoring out the influence of skating technique on performance. Despite the difference in motor patterns, researchers have suggested that the WAT is an appropriate test since it replicates the fatigue patterns experienced by hockey players during on-ice anaerobic tests (Cox et al., 1995). Further, researchers have found that measures of peak power derived from the WAT demonstrate good test-retest reliability (Vandewalle et al., 1987). Nevertheless, the differences among researchers regarding the most appropriate and accurate test of anaerobic fitness has resulted in coaches and trainers using a variety of combinations of on-ice and off-ice tests in an attempt to evaluate their players.

Although few studies have attempted to examine the influence of anaerobic power and capacity on skating performance, a recent study by Allinger & Van den Bogert (1997) indicated the importance of instantaneous and average power in speed skating. The researchers found that steady state skating velocity and the range of skating techniques used to achieve the same velocity in speed skating is limited by instantaneous and average power (Allinger & Van den Bogert, 1997). Further, Allinger & Van den Bogert (1997) proposed that the model could be applied to all skating sports, including ice hockey.

The skating model was designed with a "piston-like" leg action originating from a point mass (center of mass) to a mass-less skate (Allinger & Van den Bogert, 1997). Anatomical and physiological constraints on the skating model included maximum leg length as well as instantaneous power and average power, respectively (Allinger & Van den Bogert, 1997). Behaviour of the skating model was determined by stroke time, glide time and leg extension velocity, which formed the input function for horizontal leg length (as function of time) (Allinger & Van den Bogert, 1997). Using sequential quadratic programming, the researchers were able to perform repeated computations to determine the effects of stroke time, glide time, leg extension velocity, instantaneous power and average power on maximum skating speed and skating technique (Allinger & Van den Bogert, 1997). Through optimization of the simulation model, Allinger & Van den Bogert (1997) found the following:

1. A number of skating techniques can be used to achieve the same steady state skating speed.
2. As skating speed increases the range of techniques decreases.
3. Either average power or instantaneous power constraints can limit the steady-state skating speed.
4. Increasing instantaneous power or decreasing the height of the center of mass increases the range of possible skating techniques.
5. Increasing average power raises the top skating speed with an accompanying reduction in the range of skating techniques.
6. It is more advantageous to increase instantaneous power through increases in strength rather than increases in the speed of leg extension.
7. Full leg extension is not necessarily optimal to reach a top speed.

Allinger & Van den Bogert (1997) discussed several limitations of this study based on their skating model. First, the skating model designed for this study assumed that the height of the center of mass of the body remained constant (Allinger & Van den Bogert, 1997). Although no studies have examined the path of motion of the center of mass in ice hockey, the assumption of a fixed center of mass is allowable for comparison of the trends only in the results. Second, the power calculations used in the model were solely mechanical and therefore neglected to consider the metabolic costs of skating with different techniques (Allinger & Van den Bogert, 1997). However, instantaneous power for the model was based on force-velocity data extracted from single leg extensions during the leg press[1] (Allinger & Van den Bogert, 1997). Further, since average power in the model was merely a function of instantaneous power, values for average power were thus based on real physiological data. Again, since the values for power are based on real subjects, the results can only be used for comparison of the relationship between power, speed and the range of techniques possible in hockey skating. Third, the double support phase of the skating stride was not included and it was assumed that there was an instantaneous transfer of weight from the push-off skate to gliding skate (Allinger & Van den Bogert, 1997). Since double support times have been shown to represent less than 15% of total stride time in ice hockey, the assumption of instantaneous weight transfer is acceptable and the results may be compared (Marino, 1979). Finally, the skating model assumed that the foot remained parallel to the ice surface, thus neglecting to account for plantar flexion angles at push-off (Allinger & Van den Bogert, 1997). Literature describing the action of plantar flexion during the push-off in ice hockey and its influence on performance is lacking. However, Marino (1983) has shown that propulsive angles of the skate that reflect an outward rotation of the hip are significantly related to stride rate, which is in turn related to acceleration. This might suggest that in ice hockey, outward rotation of the hip increases propulsive angles of the skate compensating for the absence of a maximal plantar flexion of the foot. Therefore, despite the limitations of their study, it is proposed that the findings of Allinger & Van den Bogert (1997) with respect to the relationship between power, skating speed and the range of possible skating techniques should be validated for the sport of ice hockey.

[1] Leg press results from Vandervoort, A.A., D.G. Sale, and J.Moroz. Comparison of motor unit activation during unilateral and bilateral leg extension. *J. Appl. Physiol.* 56:46-51, 1984.

Purpose

The purpose of this study was to predict on-ice acceleration in elite ice hockey players using peak anaerobic power from the Wingate anaerobic test and kinematic variables from a three dimensional analysis of the biomechanics of skating technique. A sub-purpose of this study was to examine the variability of skating technique at the elite level.

Preliminary Work

Prior to data collection for the current research study, the researcher piloted all of the procedures to be used. During this time, the operation and set-up of the filming equipment was tested and the taping procedures were rehearsed and perfected. Further, the kinematic variables identified through previous research studies were identified, defined and tested following the data collection.

Methods

Thirty-seven (N = 37) elite male hockey players from the Florida Panthers (n = 18) and Los Angeles Kings (n = 19) "Prospects Camp" participated in the study. All procedures for the research study were approved by Ethics Advisory Committee to the Senate Research Committee at Lakehead University in Thunder Bay, Ontario. The players were explained the experimental protocol and informed of the associated risks of participation prior to obtaining their written consent. Prior to the completion of physical testing, anthropometric measurements, including height and weight, were determined and recorded. The subjects completed a thirty second[2], maximal intensity Wingate anaerobic test on a modified Monark™ cycle ergometer –

[2] This length of test is appropriate, despite some researchers stating that 30s. is too short to exhaust anaerobic energy stores, as hockey players do not completely exhaust anaerobic stores (Vandewalle et al., 1987).

Model # 1234, against a resistance of 0.095 kg·kg bodyweight^{-1}. One week later, the players performed two maximal, on-ice accelerations over a distance of twenty meters, while being taped by two, Panasonic™ CL-350 digital cameras.

Testing Sequence

The players, dressed in gym apparel, were asked to refrain from eating or drinking (except water) for two hours prior to reporting to the testing area. As part of the "Pro-Camp," the players were required to perform a battery of physical tests at the request of their respective strength and conditioning coaches. The physical tests that were performed, a brief description of the test protocol and the order of testing may be found in Table 1. Time restrictions limited the physical testing to one day and only one session, therefore, the rest period between the estimated VO_2 max test and the WAT was maximized (approximately thirty minutes) by placing these two tests as far apart as possible.

Table 1: Battery of tests performed by players

Name of Test	Description of Test
1. Height and Weight	N/a
2. Bench Press[a]	Number of repetitions with 185 lbs.
3. Estimated VO_2 Max - bicycle	Max. 15 min. or Max. HR prior to last stage
4. Rest	8-10 minutes
5. Sit-ups	Rhythm of metronome to exhaustion or break in rhythm
6. Sit and Reach Flexibility	N/a
7. Wingate Anaerobic Test	30s. maximal test at 0.095kg·kg BW^{-1}
8. Rest	8-10 minutes
9. Standing Broad Jump[b]	Maximal distance of two foot hop

[a] - Denotes test was only done by Florida Panthers players
[b] - Denotes test was only done by Los Angeles Kings players

Procedures - Wingate Anaerobic Test

Before beginning the measurement phase of the WAT, the players were given a ten-second acceleration phase, during which time they were told to begin pedalling slowly, gradually increasing to maximum speed in the final two seconds of the countdown. At the end of the ten-second countdown, the resistance (0.095 kg·kg bodyweight^{-1}) was applied to the flywheel of the bicycle and the measurement phase began. During the measurement phase, the players pedalled maximally against the prescribed resistance for a duration of thirty seconds. Following the conclusion of the measurement phase, the player was told to pedal at a low intensity for three to five minutes to return the body to its resting state. All players were given verbal encouragement throughout the test to obtain their best performance. Peak anaerobic power[3] (AnP) was calculated and recorded as the highest anaerobic power value produced during any of the five-second intervals. Anaerobic capacity[4] was also calculated and recorded as the total amount of work done in the thirty-second measurement phase, however these values were not used further in this research study.

[3] Peak AnP (kg·m·5s^{-1}) = [rev. max in 5 s x D/r (m) x resistance (kg)]/ time (5 s); where rev. max in 5 s = highest number of revolutions during any of the five second intervals, D/r = the distance that the flywheel travels per revolution (6 m) (Adams, 1994)

[4] AnC (kg·m·30s^{-1}) = [total rev. in 30 s x D/r (m) x resistance (kg)]/ time (30 s); where rev. total in 30 s = total number of revolutions during thirty seconds, D/r = the distance that the flywheel travels per revolution (6 m) (Adams, 1994)

Procedures - On-ice Accelerations

One week[5] following the off-ice physical testing, the players reported to the arena to perform their on-ice accelerations. Of the thirty-seven players who completed the WAT testing, only thirty (Florida Panthers, n = 14; Los Angeles Kings, n = 16) completed the on-ice accelerations. The players performed the on-ice accelerations unobstructed, wearing tight clothing of contrasting colours with no ice hockey equipment except for their sticks, elbow pads and helmets. These pieces of equipment were necessary protection for the players in the event of a fall during or upon completion of one of the accelerations. The Los Angeles players were tested first, followed by the Florida players, with both teams performing their accelerations in different skating "lanes"[6].

The testing protocol for the on-ice accelerations is listed in Table 2. Each player began with five minutes of skating at low to medium intensity skating, in order to raise their body's core temperature and prepare the specific muscles to be used in the maximal accelerations. The second phase allowed the players a period of up to five minutes to stretch those muscles that were to be active during the accelerations. The second pre-exercise phase, consisted of three to five minutes of low to medium intensity skating, interspersed with four to five sprints or accelerations, to allow the players to prepare for the measurement phase.

[5] This was the most suitable time for the teams to have their players tested on the ice.
[6] To reduce the resistance of ice friction associated with ice that has been heavily travelled.

Table 2: On-ice acceleration test protocol

Period	Time Length	Activity
Pre-Exercise I	5 minutes	Skating at low-medium intensity
Stretch	5 minutes	All major muscles; focussing on quadriceps, hamstrings, groin, calves
Pre-Exercise II	3-5 minutes	Skating at low intensity, with 4-5 sprints of 4-5 seconds
Measurement I	20 meters	Maximal acceleration from stationary position, throughout full distance
Recovery	3-5 minutes	Skating at low intensity; light stretching
Measurement II	20 meters	Maximal acceleration from stationary position, throughout full distance
Cool down	3-5 minutes	Skating at low intensity

The measurement phase consisted of a timed, maximal acceleration over twenty meters, using a photoelectric timing system located at the start and finish of the skating lane. Players were told to get into a stationary "Ready" position and then began accelerating from a front start position[7] at the "Go" command. To allow for maximal regeneration of the anaerobic energy system (glycolytic and phosphagen), a recovery phase of three to five minutes of skating at low intensity followed by complete rest was given prior to performance of the second measurement phase (Bompa, 1994). The procedures for measurement phase II were performed exactly as the first measurement phase. Following the second measurement phase, players were given a cool down period of three to five minutes of low intensity skating to allow their bodies to recover to their resting state.

[7] Research has shown the front start to be the superior starting technique (Marino, 1979).

Videography

The two Panasonic™ CL-350 digital video cameras, sampling at a frequency of 60 Hz were mounted on Peak Performance™ pan/tilt heads then fixed to a surveying tripod using a tribrach adapter and a non-optical Topcon™ tribrach. Both cameras were then gen-locked and synchronized using a Peak Performance™ Event Sychronization Unit (ESU) and a SMPTE™ time code generator. To minimize perspective error associated with video analysis, the cameras were set-up approximately forty meters apart, at a distance of fifteen meters from the direction of travel, converging at the midpoint of the twenty meter field width (see Figure 1).

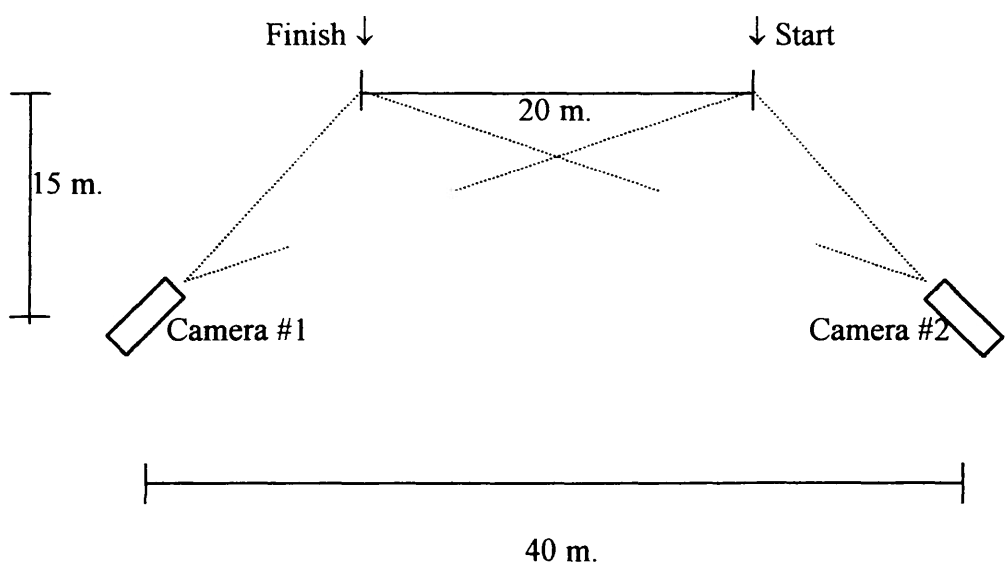

Figure 1: Camera orientation for on-ice acceleration

Following the completion of the on-ice accelerations in each lane, calibration poles were filmed at three locations (start, middle and end of the twenty meter length) using the procedures outlined by Peak Performance™ (3D Pan & Tilt Module©, Version, 1.0, May 1995) for calibrating a three-dimensional pan & tilt space.

Video Analysis

The faster of the two trials for each player, as measured by the photoelectric timer, was selected for further analysis. The two camera views were digitized using the Peak Performance™ 3D Video Analysis System and a 23-point spatial model (see Appendix A). Starting with the first push-off, the spatial model was digitized at every frame for the first five skating strides. To minimize the measurement error associated with digitization, a 4^{th} order Butterworth optimal[8] frequency filter was used to condition the raw data from both camera views. Once the data was smoothed, a direct linear transformation (DLT) using the calibration pole measurements and pan & tilt angles recorded by the tribrach heads was used to combine the two, 2D views, to produce a three-dimensional image.

[8] Jackson Knee Method

Next, the center of mass parameters[9] and kinematic variables of interest were defined (see Appendix B) and then calculated using the "3D Parameter Calculation" command in the Peak5™ 3D Pan & Tilt software. Joint angles (see Figure 2) were used to calculate the internal angle between two connected segments on a plane with values ranging between 0 and 180 degrees (Peak Performance™ User's Guide©, Version 5.3, 1995).

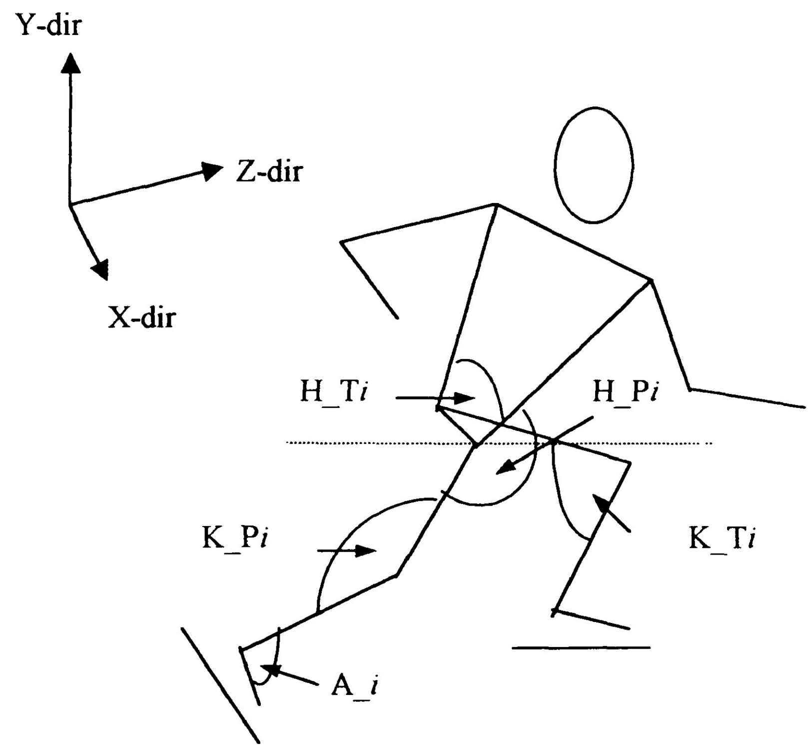

Figure 2: Joint angles (saggital view)

[9] Using the joint centers and percentage of mass distributions given by Hinrich (1988).

Segment angles (see Figure 3) were used to determine the internal angle between two unconnected segments (Peak Performance™ User's Guide©, Version 5.3, 1995).

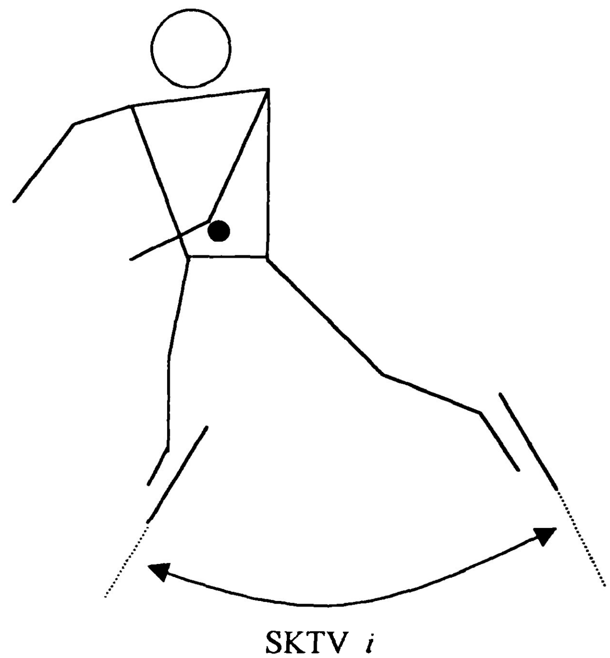

Figure 3: Segment angles (transverse view)

Finally, segment-to-plane angles (see Figure 4, Figure 5, Figure 6) were used to calculate the angle between a segment and a defined plane (Peak Performance™ User's Guide©, Version 5.3, 1995).

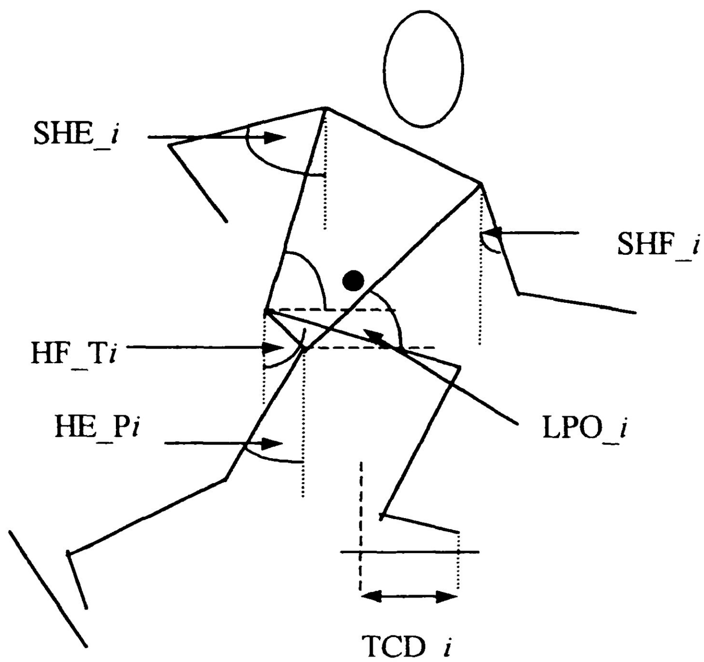

Figure 4: Segment-to-plane angles (saggital view)

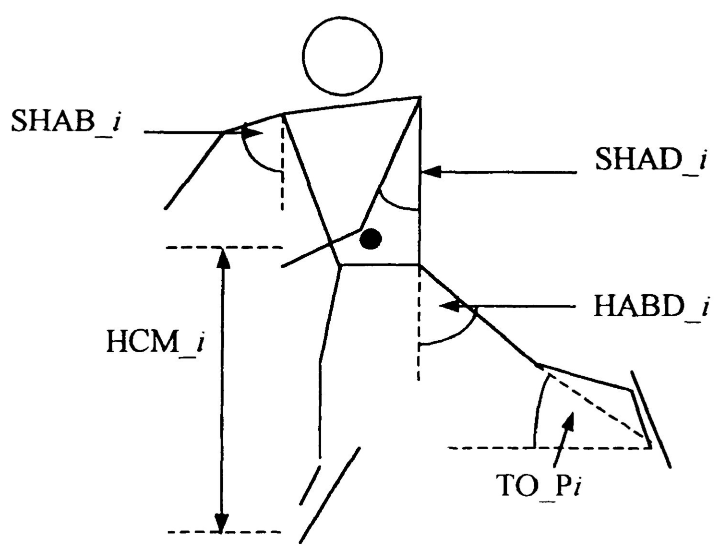

Figure 5: Segment-to-plane angles (frontal view)

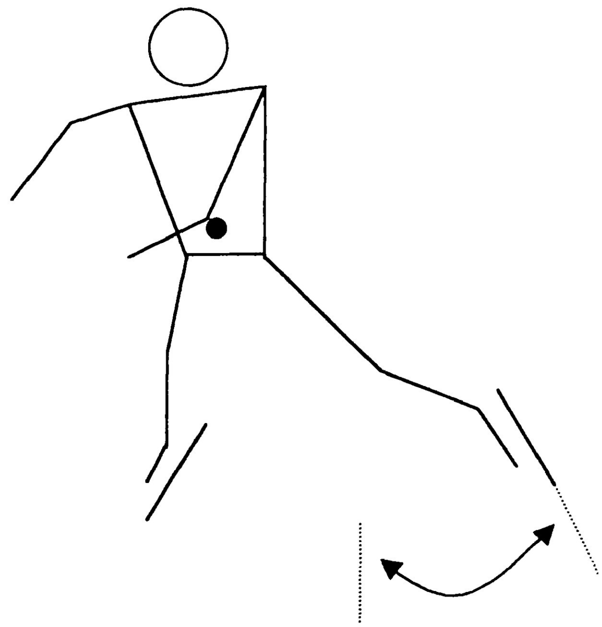

Figure 6: Segment-to-plane angles (transverse view)

The origin of the Y direction was translated from the center of mass to the right skate tip, such that the height of the center of mass could be calculated at touchdown (See Figure 5). For a more detailed description (based on spatial model) of the joint, segment and segment-to-plane angle set-up, refer to Appendix C.

Time, instantaneous velocity and average acceleration at 1.52, 3.03, 4.54 and 6.06 m were recorded for each player, while kinematic data was collected at push-off[10] and touchdown[11] for the first five (5) strides.

[10] Moment the skate tip loses contact with ice surface at completion of the push-off phase.
[11] Moment recovery skate contacts the ice in its starting position, completing a skating cycle.

Statistical Analyses

Descriptive Statistics

Descriptive statistics, including means, standard deviations, ranges, skewness and kurtosis were computed for all continuous variables. Independent samples t-tests were used to test for significant differences between the two teams and between the forwards and defencemen on either the time taken to skate six meters or peak anaerobic power. All descriptive statistics were performed using SPSS™, Version 9.0.

Factor Analyses

Exploratory principal component factor analysis (PCA) was used to a) filter the set of predictor variables by eliminating confounding kinematic variables from further analyses, and b) identify the underlying relationships between groups of kinematic variables which represent important characteristics of ice hockey skating. All kinematic variables for each stride, with the exception of peak anaerobic power and time, velocity and average acceleration measurements at 1.54 m, 3.03 m, 4.54 m, 6.06 m, were entered into the initial PCA. The exploratory PCA was then used to systematically remove those kinematic variables with no factor loadings or with weak factor loadings (<.60), and those variables exhibiting multicollinearity that were not identified prior to entry into the PCA (McPherson, Montelpare & Puumula, 1999). The final, PCA produced a factor structure of agglomerated kinematic variables with factor loadings greater than (0.60) that together described the important characteristics of ice hockey skating technique. The factor structure consisted of three latent variables, each describing a distinct component of skating technique. The latent variables highlighted "isolated variables" in which only one stride within a kinematic measure exhibited a strong factor loading and "variable sets" in which repeated (two or more) strides within a kinematic measure demonstrated strong factor loadings. Isolated variables demonstrated the importance of critical skating movements at specific instances in time (i.e. ankle, knee and hip angle on the first push-off), whereas variable sets emphasized the progression of a kinematic variable on subsequent strides (i.e. hip angle at touchdown on stride one, two, three, and five). The sign (+, –) of each factor loading within a latent variable was used to interpret the relationship between each kinematic variable and the time taken to skate six meters. The relationship between the factor loading and the dependent measure time to skate six meters was then used to determine the tendency of each kinematic variable in order to optimize on-ice acceleration. All factor analyses were performed using the factor analysis command "proc factor" in SAS™, Version 6.12.

Transposed Variables and the Power Function

The "variable sets" identified within the latent variables included a minimum of two and maximum of five factor loadings for any specific kinematic variable. Factor loadings for sample strides within a variable set were primarily in series (i.e. strides one, two and three), whereas some variable sets included individual strides that were not in series with the remaining sample strides (i.e. strides one, two, three and five). A log-log transformation of the power function (see Equation 1 and Equation 2) transposed the raw scores, for the strides that loaded in series within a variable set, into a single composite score (Stevens, 1957).

Equation 1: Power function

$$\psi = K + \phi^{\beta}$$

Equation 2: Log-log transformation of the power function

$$\mathrm{Log}\,\psi_i = \mathrm{Log}\,K + \beta\,\mathrm{Log}\,\phi_i$$

where, $K = 1$

ϕ_i = stride interval (1-5)

ψ_i = raw score for given interval

β = slope of line of best fit for transformed data set

Each raw score (i.e. $\psi_{K\_T2} = 100.34$, $\psi_{K\_T3} = 97.34$) within a variable set was first assigned a corresponding interval (i.e. $\phi_{K\_T2} = 1$, $\phi_{K\_T3} = 2$). Next, the log-log transformation was applied to the raw scores and corresponding interval to create a transformed data set (i.e. {log $\phi_{K\_T2} = 0$, log $\psi_{K\_T2} = 2.00$}, {log $\phi_{K\_T3} = 0.301$, log $\psi_{K\_T3} = 1.99$}). Finally, by setting $K = 1$ and plotting the transformed data set, linear regression was used to determine the slope (β) of a line of best fit through the data set, originating from the origin (0,0). The slope of the line was used as a single composite score which represented an evaluation of the progression of a player's skating technique over a series of strides on a specific kinematic variable set (see Figure 7).

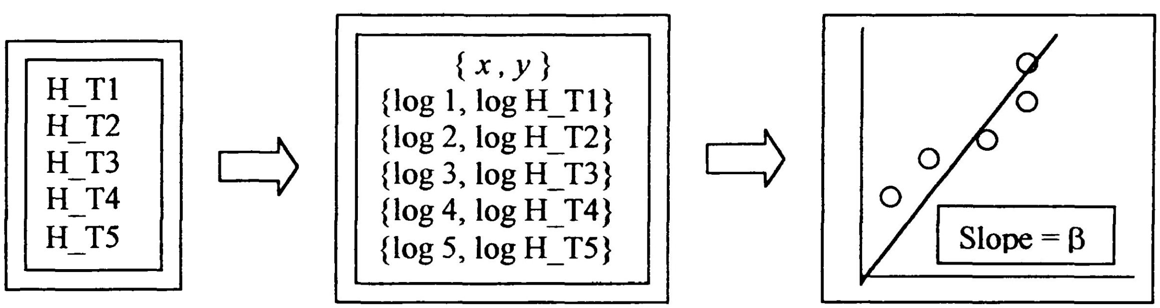

Figure 7: Depiction of the log-log transformation of a variable set

The composite scores were then recoded and entered into SPSS as a new variable. This procedure was repeated for each variable set identified by the PCA, using only the strides that loaded on a latent variable in series. Individual strides that were not in series but were a part of the variable set (i.e. stride 5 for a series: 1,2,3,5) were not transposed using the power function, however, these individual strides were included as isolated variables in the regression analysis. All composite scores for the variable sets were generated using the descriptive statistics procedures of "proc univariate" in SAS™, Version 6.12.

Regression Analysis

Multiple regression analysis using a backward stepwise approach was used to determine the set of variables that best predict the time taken to skate 6.06 m. The variables entered into the regression analysis included, height, weight, peak anaerobic power (normalized for bodymass) and all "isolated variables" and transposed "variable sets" with factor loadings of greater than (.60) identified by the final exploratory PCA. Isolated variables that were inconsistent with the characteristics of a clearly defined latent variable within the factor structure were excluded from the regression analysis. The regression analysis was performed using SPSS™, Version 9.0.

Variability of Skating Technique

Estimates of skewness and kurtosis were used to determine the variability in skating technique among the subjects in this study. More specifically, skewness and kurtosis was calculated for each kinematic variable identified within the PCA and the set of variables which best predicted the time taken to skate six meters. A skewness value of zero indicated that the mean and median scores for a kinematic measure were equal and the distribution, symmetrical. Likewise, a kurtosis value of zero indicated that the scores for a kinematic measure were normally distributed with equal variance above and below the mean score. Positive and negative values for skewness indicated the respective direction of skewness and the magnitude of the skewness value determined the degree of skewness (Diekhoff, 1992). Similarly, positive and negative kurtosis values indicated leptokurtic (small amount of variance about mean) and platykurtic (large amount of variance about mean) distributions, respectively, with the degree of kurtosis determined by the magnitude of the respective value (Diekhoff, 1992).

Results

Video data could not be obtained for six of the players, and three of the players started with a left foot push-off, therefore, the analysis was limited to twenty-one (N = 21) players who completed both the WAT and the on-ice accelerations.

Descriptive Statistics

Descriptive statistics of the physical characteristics for the participants in this study are shown in Table 3. Means, standard deviations, minimums and maximums for all raw kinematic data, along with estimates of skewness and kurtosis, may be found in Appendix D.

Table 3: Physical characteristics of the players (N = 21)

Variable	Mean	S.D.	Minimum	Maximum
Age (years)	19.95	1.80	18	24
Height (m)	1.87	0.05	1.73	1.93
Weight (kg)	91.19	5.00	78.0	100.0
Peak Anaerobic Power ($W \cdot kg^{-1}$)	12.21	1.02	10.55	15.07
Anaerobic Capacity ($W \cdot kg^{-1}$)	9.19	0.49	7.86	10.12

The mean time taken to skate six meters was 1.22 s (S.D. = 0.11), with a mean instantaneous velocity at six meters of 6.44 $m \cdot s^{-1}$ (S.D. = 0.32). The mean average acceleration over the six meters was 5.33 $m \cdot s^{-2}$ (S.D. = 0.58). The mean time, mean instantaneous velocity and mean average acceleration values at 1.52 m, 3.03 m, 4.54 m, 6.06 m are listed in Table 4.

Table 4: Time, Velocity and Average Acceleration (X ± SD)

Variable	Distance (meters)			
	1.52	**3.03**	**4.54**	**6.06**
Time to Skate (s)	0.41 ± 0.06	0.71 ± 0.08	0.97 ± 0.09	1.22 ± 0.11
Instantaneous Velocity ($m \cdot s^{-1}$)	4.68 ± 0.51	5.37 ± 0.27	5.92 ± 0.35	6.44 ± 0.32
Avg. Acceleration ($m \cdot s^{-2}$)	11.86 ± 2.89	2.21 ± 1.29	2.12 ± 1.12	2.09 ± 1.67

An independent samples t-test revealed no significant differences between players from the Florida Panthers (n = 12) and Los Angeles Kings (n = 9) on measures of peak anaerobic power ($t(19) = -1.036$, $p>0.05$) or the time taken to skate six meters ($t(19) = 0.928$, $p>0.05$). Similarly, no significant differences were found between forwards (n = 13) and defencemen (n = 8) on peak anaerobic power ($t(19) = -0.097$, $p>0.05$) or the time taken to skate six meters ($t(19) = 0.725$, $p>0.05$).

Factor Analyses

The exploratory PCA's resulted in the removal of nine of the seventeen original kinematic measures. Using the eight remaining kinematic measures collected over five strides (fifty variables), the final, PCA produced three distinct latent variables with factor loadings of greater than (.60). Within the three latent variables, six "variable sets" and eight "isolated variables" were found. Of the six observed variable sets, three sets included all skating strides loading in series, and three sets contained individual strides that were not in series with the remaining strides. The kinematic measures hip abduction angle at push-off, stride length, and propulsive time, formed variable sets in which all skating strides within the set loaded in series. However, the remaining variables sets for hip angle at touchdown, take-off angle, and knee angle at touchdown included individual strides that were not in series with the remaining strides in the variable set. All of the variable sets loaded on the first latent variable except, knee angle at touchdown, which loaded on the third latent variable. Two of the eight isolated variables, toe to center of mass distance at touchdown on the third stride, and knee angle at touchdown on the fourth stride appeared in the first latent variable. The second latent variable included only isolated variables. The isolated variables were ankle angle, knee angle and hip angle at push-off for the first stride, hip angle at push-off for the fifth push-off, and toe to center of mass distance at touchdown on the fifth stride. Finally, the only "variable isolation" for the third latent variable was the take-off angle at push-off for the first stride. The variables and their factor loadings for each of the three latent variables are listed in Table 5.

Table 5: PCA latent variables and their respective factor loadings

Latent Variable					
1		*2*		*3*	
Variable	*Loading*	*Variable*	*Loading*	*Variable*	*Loading*
H_T1	.781	H_P1	.838	K_T2	.636
H_T2	.679	H_P5	.733	K_T3	.778
H_T3	.913	K_P1	.691	TO_P1	.702
H_T4	.792	A_P1	.805		
H_T5	.782	TCD_T5	-.688		
HABD_P2	-.698				
HABD_P4	-.617				
HABD_P5	-.624				
TO_P3	.692				
TO_P4	.791				
TO_P5	.771				
SL_1	-.653				
SL_2	-.627				
SL_3	-.715				
SL_5	-.721				
PT_2	-.682				
PT_3	-.759				
PT_4	-.628				
TCD_T3	.641				
K_T4	.602				

The eigenvalues, percentage of variance explained and cumulative variance explained for the three latent variables is listed in Table 6.

Table 6: Eigenvalues and variance explained by the three latent variables

Latent Variable	**Eigenvalue**	**% of Variance Explained**	**Cumulative % of Variance Explained**
1	14.26	28.52	28.52
2	7.78	15.55	44.07
3	6.04	12.08	56.15

Power Function and the Transposed Variable

Descriptive statistics for the six transposed variable sets, hip angle at touchdown, hip abduction angle at push-off, take-off angle, stride length, propulsive time and knee angle at touchdown are listed in Table 7.

Table 7: Descriptive statistics for transposed variables

Variable	Strides	Mean	S.D.	Skewness	Kurtosis
H_T	1 - 5	3.474	0.078	-1.795	4.926
HABD_P	4, 5	3.968	0.548	-0.025	-0.757
TO_P	3 - 5	4.173	0.057	-0.736	0.902
SL_	1 - 3	0.380	0.107	-0.502	-0.551
PT_	2 - 4	-1.409	0.085	-0.339	-0.114
K_T	2, 3	6.656	0.083	-1.122	1.481

Regression Analysis

Backward stepwise multiple regression analysis was used to identify the variables that best predicted the time taken to skate six meters. Variables entered into the regression analysis included, height, weight, peak anaerobic power and all variables (transposed sets and isolations)[12] identified by the PCA listed previously in Table 5. The variables that best predict the time taken to skate six meters can be found in Equation 3.

Equation 3: Regression equation for time to skate six meters

$$Y = 0.291 + 0.845\,X_1 - 0.016\,X_2 + 0.007\,X_3 + 0.007\,X_4 + 0.453\,X_5$$
$$- 1.500\,X_6 - 1.688\,X_7 - 0.006\,X_8 - 0.004\,X_9$$

where:

X_1 = Player height

X_2 = Peak anaerobic power (normalized)

X_3 = Knee angle – 1st push-off

X_4 = Transposed variable – hip abduction (Stride 4, 5)

X_5 = Transposed variable – propulsive time (2, 3, 4)

X_6 = Transposed variable – stride length (1, 2, 3)

X_7 = Toe to center-of-mass distance – 3rd touchdown

X_8 = Hip angle – 1st push-off

X_9 = Hip abduction – 2nd push-off

[12] Except H_P5 and TCD_T5, which were inconsistent with the characteristics of the second latent variable.

The multiple correlation coefficient (R = .976) for the above regression equation was significantly different from zero (F(9,20) = 24.933, p<0.001), with 95.3% (S.E.E. = .031) of the variance in the time to skate six meters being explained by the set of nine predictors. After adjusting for shrinkage due to the small sample size and large set of predictors in this study, the prediction equation accounted for 91.5% of the variance in the time taken to skate six meters. The results of the test of significance for the unstandardized (*b*) and standardized coefficients (β) are listed in Table 8.

Table 8: Coefficients and t-values for regression analysis variables

Variable	*b*	S.E. *b*	β	t	Sig. T
(Constant)	0.291	0.927		0.314	0.759
HT	0.845	0.302	0.379	2.796	0.017
An_P	-0.016	0.007	-0.152	-2.238	0.047
K_P1	0.007	0.003	0.555	2.619	0.024
TV_HABD	0.007	0.027	0.350	2.529	0.028
TV_PT	0.453	0.125	0.363	3.606	0.004
TV_SL	-1.500	0.174	-1.848	-8.63	0.000
TCD_T3	-1.688	0.382	-0.961	-4.415	0.001
H_P1	-0.006	0.001	-0.697	-4.366	0.001
HABD_P2	-0.004	0.002	-0.267	-2.267	0.045

Variability of Skating Technique

Estimates of skewness and kurtosis were used to determine the variability of the players skating technique on those variables identified by the PCA and the regression analysis. A critical value of positive one (1) for skewness or kurtosis represented a positively skewed or leptokurtic distribution, while a critical value of negative one (-1) represented a negatively skewed or platykurtic distribution. The variability estimates for the kinematic measures loading on the first latent variable of the PCA are listed in Table 9.

Table 9: Estimates of skewness and kurtosis for the variables in the first latent variable

Variable	Skewness	Kurtosis
H_T1	-0.526	0.102
H_T2	-0.970	1.847
H_T3	-0.803	1.239
H_T4	-1.411	4.213
H_T5	-1.098	1.267
HABD_P2	0.142	-0.288
HABD_P4	0.281	-0.246
HABD_P5	0.612	-0.554
TO_P3	-0.350	-0.956
TO_P4	-0.940	1.666
TO_P5	-0.232	-0.322
SL_1	-0.736	1.086
SL_2	0.607	0.858
SL_3	0.007	-1.251
SL_5	-0.487	-1.032
PT_2	0.368	-0.677
PT_3	-0.135	-0.828
PT_4	-0.190	0.143
TCD_T3	1.134	3.007
K_T4	0.269	0.153

All of the factor loadings for the variable set, hip angle at touchdown, were negatively skewed and with the exception of the first stride, leptokurtic in distribution. The factor loadings for the set of hip abduction angles at push-off, however, were positively skewed with a mildly platykurtic distribution. The take-off angles used during push-off were mildly skewed in the negative direction for all strides. Strides three and five were found to have a platykurtic distribution and stride four, a leptokurtic distribution. The stride length used during the acceleration was rather leptokurtic in the initial strides, yet the variance in the length of stride increased during the later strides. Propulsion times for the players showed very little skewness and moved from a moderately platykurtic distribution to a mesokurtic distribution by the fifth stride. The players showed little variance in the distance between the toe and center of mass at touchdown on the third stride, yet some of the players caused the distribution to distinctly skew in the positive direction. Finally, the player's knee angle at touchdown of the fourth stride, followed a mesokurtic distribution with a very small amount of skewness in the positive direction.

The variability estimates for the kinematic measures loading on the second latent variable can be found in Table 10.

Table 10: Estimates of skewness and kurtosis for the variables in the second latent variable

Variable	Skewness	Kurtosis
H_P1	-1.052	1.401
K_P1	-1.195	2.860
A_P1	-0.419	-0.399

All of the variables loading on factor two were skewed in the negative direction with the hip and knee angle at push-off having a leptokurtic distribution, and ankle angle at push-off having a moderately platykurtic distribution.

Finally, the variability estimates for the kinematic measures loading on the third latent variable of the PCA can be found in Table 11.

Table 11: Estimates of skewness and kurtosis for the variables in the third latent variable

Variable	Skewness	Kurtosis
K_T2	0.286	-0.171
K_T3	-0.951	1.112
TO_P1	1.232	3.190

The skewness and kurtosis for the knee angle at touchdown for the second and third strides differed considerably. For the second stride, the knee angles used at touchdown were skewed mildly in the positive direction, whereas the knee angles at touchdown for the third stride were largely skewed in the negative direction. Similarly, the somewhat platykurtic distribution of the knee angles at touchdown for the second stride was very different from the very leptokurtic distribution of the knee angles at touchdown for the third stride. The angle of take-off on the first stride was positively skewed and highly leptokurtic in distribution.

The skewness and kurtosis estimates for the variables identified by the regression analysis as the best set of predictors for the time taken to skate six meters are listed in Table 12.

Table 12: Estimates of skewness and kurtosis for the predictors of time to skate six meters

Variable	Skewness	Kurtosis
HT	-1.497	3.279
AnP	0.815	1.851
K_P1	-1.195	2.860
TV_HABD	-0.025	-0.757
TV_PT	-0.502	-0.551
TV_SL	-0.339	-0.114
TCD_T3	1.134	3.007
H_P1	-1.052	1.401
HABD_P2	0.142	-0.288

With the exception of hip abduction angle at push-off, all kinematic measures found to be significant predictors of the time taken to skate six meters were leptokurtic in distribution. Similarly, the height of the players and their peak anaerobic power were also leptokurtic in distribution. However, the stride characteristics, stride length and propulsive time, found to be significant predictors of the time taken to skate six meters were relatively platykurtic in distribution. The skewness and kurtosis estimates for the remaining variables can be found in Appendix D.

Discussion

The heights and weights of the players from the Florida Panthers and Los Angeles Kings who participated in this research study were similar to those of professional hockey players from the National Hockey League. The average height of the thirteen forwards participating in the study was 1.86 m (S.D. = 0.05) and the average weight was 90.31 kg (S.D. = 5.19). The average height and weight for the eight defencemen who participated in the study was 1.90 m (S.D. = 0.03) and 92.63 kg (S.D. = 4.63), respectively. Twist & Rhodes (1993) found that the average height for veteran NHL forwards was 1.89 m (S.D. = 0.04), with an average weight of 92.9 kg (S.D. = 3.82). Similarly, Rhodes, Cox & Quinney (1988) found that the average height and weight for fourty NHL forwards was 1.83 m (S.D. = 0.05) and 87.1 kg (S.D. = 5.60), respectively. For veteran defencemen, Twist & Rhodes (1993) reported an average height of 1.89 m (S.D. = 0.05) and an average weight of 94.14 kg (S.D. = 4.23). Likewise, Rhodes et al. (1988) reported an average height and weight for twenty-seven defencemen of 1.86 m (S.D. = 0.05) and 90.30 kg (S.D. = 4.30), respectively. The similarities observed in height and weight to previous research were expected, as all of the players in this research study were members of NHL organizations.

The peak anaerobic power results obtained from the Wingate anaerobic test in this study were also similar to the results of NHL players that have been reported in previous literature. The players in this study cycled against a resistance of 0.095 kg·kg bodyweight^{-1}, resulting in an overall mean score for peak anaerobic power of 12.21 W·kg^{-1} (S.D. = 1.02). There were no significant differences (t (19) = -0.10, $p > 0.05$) found in this study between the peak anaerobic power of the forwards (X = 12.19 W·kg^{-1}, S.D. = 1.22) and the peak anaerobic power of the defencemen (X = 12.24 W·kg^{-1}, S.D. = 0.68). Rhodes, Cox & Quinney (1988) and Smith, Quinney, Steadward, Wenger & Sexsmith (1982) also reported no significant difference in peak anaerobic power scores between forwards and defencemen. Rhodes, Cox & Quinney (1988) reported that the mean peak anaerobic power score for twenty-seven NHL defencemen and fourty NHL forwards cycling against a resistance of 0.090 kg·kg body weight^{-1} was 12.04 W·kg^{-1} (S.D. = 1.50) and 12.00 W·kg^{-1} (S.D. = 1.19), respectively. Smith et al. (1982) reported peak anaerobic power scores of 11.7 W·kg^{-1} (S.D. = 1.0) and 11.5 W·kg^{-1} (S.D. = 0.4) respectively for forwards and defencemen of the 1980 Canadian Olympic Hockey Team. The resistance used by Smith et al. (1982) was based on bodyweight as well as leg volume, and therefore might explain the somewhat lower peak anaerobic power values when compared to the values reported by Rhodes et al. (1988) and those observed in the present study.

The mean time taken by the players to skate 6.06 meters in this study was 1.22 s (S.D. = 0.11), with times ranging from 1.07 s to 1.40 s. Marino (1983) reported a much slower average time of 1.95 s (S.D. = 0.13) to skate a distance of six meters. In 1956, St. Denis reported that high school players were able to skate a distance of twenty-four feet (7.27 m) in an average time of 1.74 s (S.D. = 0.12). The disparity between the findings of the present study and of previous literature in the time taken to skate six meters may be explained by differences in the expertise (skating ability and physical fitness) of the participants and the methods in which time was measured. While fourteen of the sixty-nine hockey skaters in his study were members of a university club hockey team and the remaining fifty-five were volunteers from intramural teams or hockey classes, Marino (1983) reported that none of the participants could be considered elite performers. St. Denis (1956) reported that all seventeen subjects in his research study were members of a "high caliber" high school hockey team. However, as members of the NHL organization, the subjects participating in the present study would be considered elite skaters when compared to subjects in previous research. Therefore, skating ability (i.e. optimization of push-off and summation of muscle forces) and physical fitness (strength and power) might explain a portion of the difference observed in the average time taken to skate six meters. Another explanation for the differences between the present study and previous research in the time to skate six meters is the method of timing. Timing of the accelerations began upon the skater's first voluntary movement and on a "GO" command, in the respective studies by Marino (1983) and St. Denis (1956). However, the timing of the on-ice accelerations in the present study began with the player's first push-off (right foot for all skaters) and therefore does not include the time taken by the players to begin and complete their first push-off.

The mean instantaneous velocity at six meters for the players in this study was 6.44 $m \cdot s^{-1}$ (S.D. = 0.32) with velocities ranging from 6.00 to 7.26 $m \cdot s^{-1}$. The mean average acceleration over the six meters was 5.33 $m \cdot s^{-2}$ (S.D. = 0.58) with a range of 4.41 to 6.47 $m \cdot s^{-2}$. Marino (1983) reported a similar mean instantaneous velocity of 5.75 $m \cdot s^{-1}$, yet a much lower mean average acceleration of 2.96 $m \cdot s^{-2}$ over the six meters. The differences in mean instantaneous velocity and average acceleration can again be attributed to differences in the skating ability and physical fitness of the players, and the method of timing the acceleration. Further, players in the present study had already attained an increased velocity upon the initiation of the timing and therefore would have an inflated average acceleration, when compared to previous research by Marino (1983) and St. Denis (1956) in which the initial velocity was zero.

Kinematics of Skating

Although kinematic data was collected for the first seven strides starting with right foot push-off, the kinematic analysis was limited to the first five strides since all players had completed five strides before having travelled a distance of six meters.

The results of the kinematic analysis of the first five strides revealed that the players tended to use short, rapid strides initially, followed by longer, slower strides in the later part of the acceleration. Average stride length increased progressively from 1.02 m (S.D. = 0.27) in the first stride to 1.85 m (S.D. = 0.23) by the fifth stride. Similarly, an increase in the first stride propulsion time from 0.245 s (S.D. = 0.028) to the fifth stride propulsion time of 0.295 s (S.D. = 0.028), resulted in a decrease in stride rate from 3.74 strides·s^{-1} (S.D. = 0.27) to 3.61 strides·s^{-1} (S.D. = 0.42), over the first five strides. After taking the average of the first three strides combined, Marino (1983) reported a slightly shorter mean stride length of 1.11 m and a slightly slower mean stride rate of 3.31 strides·s^{-1}. The difference in stride length could be attributed to the differences in the height of the subjects, and the difference in the stride rate is likely due to differences in the leg power and skating experience.

In the present research study, the average double support time was negative during the first four skating strides, which indicated that for most players no glide phase existed in which both skates were simultaneously in contact with the ice surface. Earlier research by Marino & Dillman (1976) suggested that no double support period existed during rapid accelerations, confirming the findings of the present study. Further supporting the findings of the present study, Marino (1979) found that during acceleration the glide phase occurs during a portion of the single support period. Propulsive time in this research study was defined as the time taken from touchdown of the skate at the end of the recovery phase to the end of the next push-off phase. The mean propulsive time increased from 0.245 s (S.D. = 0.03) in the first stride to 0.295 s (S.D. = 0.03) by the fifth stride. Marino (1983) reported that the average single support time for the first three strides was approximtely 0.262 s (S.D. = 0.03). However, since there was no period of double support during the first four strides in this study, the propulsive time by definition is synonymous to single support time as defined by Marino (1983). Therefore, the propulsive times found in the present study, are similar to those reported by Marino (1983).

During forward acceleration, the players increased the degree of forward lean and hip flexion at touchdown, which caused a decrease in the hip angle (angle between the torso and thigh) at touchdown. Mean hip angle at touchdown for the first stride was 100.79° (S.D. = 10.63), whereas the mean hip angle at touchdown during the fifth stride was 81.28° (S.D. = 9.00). The angle of the hip at push-off also decreased during the acceleration as a result of increased forward lean and decreased hip extension. At the end of the first push-off, mean hip angle was 159.35° (S.D. = 13.13) and following the fifth push-off, mean hip angle increased to 142.96° (S.D. = 9.85). Although lean angle at push-off and touchdown as well as hip flexion and extension have been reported separately in previous research studies, hip angle (angle between torso and thigh in 3D) at push-off and touchdown was used in this research study to represent both torso lean and thigh position. Nevertheless, the analysis of the lean angle at push-off and touchdown in this study were similar to values reported previously by Marino (1983). Marino (1983) reported a mean score for lean angle at push-off and touchdown, when averaged over the first three strides, of 41.76° (S.D. = 7.52) and 43.44° (S.D. = 20.65), respectively. The lean angle at push-off in this study ranged between 43.31° (S.D. = 8.67) and 31.15° (S.D. = 5.96), and between 46.56° (S.D. = 6.96) and 54.04° (S.D. = 7.55) at touchdown. Further, Marino

(1983) reported a mean hip angle of 155.84° (S.D. = 9.75) at push-off over the first three strides, which is consistent with the findings of this study mentioned previously.

Increased hip abduction rather than hip extension was observed at push-off, throughout the acceleration. Mean hip abduction increased from 5.93° (S.D. = 3.43) in the first push-off to 16.75° (S.D. = 3.78) by the fifth push-off. On the other hand, hip extension decreased from 26.16° (S.D. = 7.66) to 22.69° (S.D. = 5.21), between the first and fifth strides, respectively. Following an analysis of the start in speed skating, de Koning, Thomas, Berger, de Groot & van Ingen Schenau (1995) concluded that as skating speed increased the amount or hip extension (as measured by displacement in Y-coordinate) decreased and the amount of hip abduction (as measured by increase in X-coordinate) increased. Similarly, Pagé (1976) reported that the average angle of leg abduction during top-speed was 30.36° (S.D. = 6.62). Therefore, the results of the present study and of previous literature indicate that skaters generate propulsion primarily through hip extension during the initial strides, yet use primarily hip abduction to create propulsion in later strides.

Knee angle at push-off remained constant throughout the acceleration with means for each stride ranging between 155.34° (S.D. = 5.46) and 158.18° (S.D. = 6.24), whereas knee angle at touchdown decreased in successive strides from 107.25° (S.D. = 5.22) in the first to 97.21° (S.D. = 4.60) in the fifth. Similar values were reported by Marino (1983), who found that knee angle at push-off was 155.23° (S.D. = 13.43) when averaged over the first three strides. Although Marino (1983) did not report knee angle values at touchdown, Pagé (1976) reported knee flexion angles ranging from 95° to 130° during forward skating. Pagé (1976) measured the angle of knee flexion prior to the start of propulsion rather than at touchdown, which might therefore explain the large range of knee flexion angles observed.

The mean height of the center of mass decreased from 0.91 m (S.D. = 0.06) at the first touchdown to 0.87 m (S.D. = 0.05) at the fifth touchdown. The decreased height of the center of mass was primarily a function of an increase in forward lean of the torso and decrease in knee angle at touchdown. Consistent with the average push-off angle (take-off angle) reported by Marino (1983), the angle of take-off with the ice-surface decreased slightly in the present study, from 53.23° (S.D. = 4.62) in the first push-off to 50.30° (S.D. = 2.91) for the fifth push-off. Researchers have suggested that a decreased height of the center of mass and take-off angle during acceleration permits a greater range of motion at the hip and knee joints and as a result, increased propulsion and skating speed (Allinger & van Den Bogert, 1997; de Koning et al. 1995; Marino 1984).

The angle between the skate blades at touchdown, or the skate-v angle, decreased considerably during the acceleration. The average skate-v angle for the first touchdown was 108.51° (S.D. = 14.08), yet this value decreased to 77.02° (S.D. = 8.78) by the fifth touchdown. The decreased skate-v angle at touchdown was a function of the decreased propulsive angle of the skate with the direction of travel. The propulsive angle of the skate decreased from 65.44° (S.D. = 9.57) in the first push-off to 53.88° (S.D. = 7.69) in the fifth push-off. Marino (1983) reported a somewhat smaller mean propulsive angle of 40.54° (S.D. = 6.20) over the first three strides. Researchers investigating the push-off in speed skating have previously reported that speed skaters used large propulsive angles during the start in speed skating in order to push-off against a fixed position (de Koning et al., 1995; van Ingen Schenau, de Boer & de Groot, 1987). However, as forward skating speed increased, push-off forces no longer were directed against a fixed position and therefore, smaller propulsive angles were used (de Koning et al., 1995; van Ingen Schenau et al., 1987).

Plantar flexion, as measured by the angle of the ankle joint at push-off, remained relatively unchanged throughout the acceleration with values ranging between 115.52° (S.D. = 7.29) and 118.18° (S.D. = 6.68) for all five strides. Although, Marino & Weese (1979) reported that skaters used "some" plantar flexion in the ice hockey skating stride, no research studies to date have examined the role of plantar flexion during the acceleration. Van Ingen Schenau et al. (1987) reported that speed skaters are taught to suppress maximal plantar flexion to avoid undesirable increases in ice friction caused by the skate tip. Therefore, further research is necessary to determine the effect of plantar flexion and skate blade shape on ice friction and skating speed during acceleration in ice hockey.

The vertical displacement of the left foot was monitored during the recovery phase of strides two, four and six. During these strides, players in this study consistently lifted their left foot between 0.19 m (S.D. = 0.06) and 0.20 m (S.D. = 0.06) above the ice surface. The vertical displacement of the foot during the recovery phase in this study is slightly greater than that (X = 0.14 m, S.D. = 0.04) reported by Marino (1983), however, these differences may have been proportional to the differences in the height of the subjects and their corresponding limb lengths. The distance between the toe of the skate and the center of mass at touchdown increased throughout the acceleration for the players in this study. The smallest toe to center of mass distance occurred at the first touchdown (X = -0.026 m, S.D. = 0.09) and the distance progressively increased to the greatest distance at the fifth touchdown (X = -0.174 m, S.D. = 0.05). The placement of the foot upon completion of the recovery phase in this study differs greatly from the findings of Marino (1983), who reported that the mean toe to hip distance for the average of the first three strides was 0.263 m (S.D. = 0.078). Although, the present research used the toe to center of mass distance instead of the toe to hip distance at touchdown, these discrepancies must be the result of differences in the calculation or interpretation of this value. It appears that most of the skaters in this study placed their recovery skate in a position which would have created a breaking force, caused them to decelerate and increased the time taken to skate the six meters. Marino (1983) hypothesized that placing the skate too far in front of the body, also shown in the present study, would delay the onset of the subsequent propulsive phase until the body was in a suitable position relative to the foot.

Analysis of the arm action during the first five strides revealed that there was little change in the amount of flexion, extension and abduction of the shoulder joints during the acceleration. Shoulder flexion at push-off ranged between –4.22° (S.D. = 16.24) and 3.42° (S.D. = 12.56), and shoulder extension ranged between 43.32° (S.D. = 11.20) and 45.53° (S.D. = 14.93), both measured from the XY plane. Shoulder abduction was consistently between 40.57° (S.D. = 12.66) and 44.72° (S.D. = 10.84) to the YZ plane throughout the acceleration. There was however, a progressive increase in the amount of adduction (as measured by the angle of abduction) at the shoulder joint from 20.12° (S.D. = 14.77) at the first push-off to 1.85° (S.D. = 12.31) at the fifth push-off. It has been suggested by hockey coaches that the arm action in ice hockey should complement and coordinate the propulsive action of the legs, although there is a lack of empirical evidence to support this claim (ASEP Youth Hockey Coaching Manual 1996; Tarasov, 1973). However, the results of the present indicate that players began with a front to back arm action and progressed to a more side to side arm action to balance the increased hip abduction and decreased hip extension during the later strides of the acceleration. Nevertheless, this is the first research study to the author's knowledge that has examined the kinematics of the upper arm during ice hockey skating, and thus further research must be done to confirm these findings.

Kinematic Variable Structure

Perhaps the greatest limitation to previous research investigating the kinematics of ice hockey skating was the grouping of kinematic data for the initial strides into a single mean score, thus concealing the uniqueness of each stride and the progression of the skating stride during acceleration. This was necessary because of the volume and complexity of collecting and analyzing kinematic data collected over numerous strides (i.e. stride 1, stride 2, and stride 3). However, recent advances in technology have allowed biomechanists to collect kinematic data over a far greater field width than possible in previous research. Further, statistical applications in biomechanics have enabled researchers to subsequently analyze this kinematic data without collapsing the information into a single performance score (McPherson, Montelpare & Puumula, 1999).

In this research study, exploratory factor analyses were used to examine the association between the kinematic variables of interest, identify the underlying relationships between groups of kinematic variables and to eliminate confounding kinematic variables from further analyses (Diekhoff, 1992). The principal components factor analysis (PCA) identified statistically parsimonious relationships between the kinematic variables and was therefore used to create a reduced set of variables that described the kinematics of ice hockey skating during acceleration (McPherson, Montelpare & Puumula, 1999; Diekhoff, 1992). Further, by identifying isolated variables and variable sets, the PCA highlighted the importance of the individual stride as well as the progression of multiple strides to the overall acceleration.

The final PCA resulted in a factor structure with three distinct latent variables, which together described the kinematics of ice hockey skating technique. The twenty-eight variables that loaded on the final factor structure accounted for more than fifty-six percent of the total variance in the fifty kinematic variables that remained in the final PCA. Although the final model explained only fifty-six percent of the total variance, it is essential to note that the remaining variance may be attributed to the individual strides within a kinematic measure that did not have factor loadings of greater than (.60). Therefore, the remaining fourty-four percent of the variance in the model was not explained by different kinematic measures, but shared by individual strides within the same kinematic measures.

Given that the first latent variable was composed of primarily variable sets, it can be concluded that this latent variable represented the progression of the skating stride during acceleration. Further, the variable sets were found within kinematic measures that researchers have previously identified as important variables for maintaining optimal propulsion during skating. In 1983, Marino suggested that although take-off angle and forward lean at touchdown and push-off were not significantly correlated with average acceleration, these measures were important factors in the optimization of both the magnitude and direction of propulsion. Similarly, de Koning et al. (1995) reported that by the eighth stride in the speed skating start, skaters moved from a "running-like" skating technique to a "gliding" technique in order to maintain an effective push-off. The researchers found that as skating speed increased, the amount or hip extension (as measured by decreases in the Y-coordinate) decreased and the amount of hip abduction (as measured by increases in the X-coordinate) increased (de Koning et al., 1995). In addition, van Ingen Schenau et al. (1987) reported that performance in speed skating was significantly correlated to the direction of the push-off force in the X-Z plane. Therefore, given that the factor loadings within this variable represented the progressive changes in the skating stride throughout acceleration in an attempt to maximize the efficiency of propulsion, the first latent variable was referred to as the *propulsion efficiency factor*. By examining the sign of the factor loadings, it can be concluded that in order to maintain propulsion efficiency, skaters must decrease (+ sign) their hip angle at touchdown and their angle of take-off, while simultaneously increasing (- sign) their hip abduction angle at push-off on successive strides. These tendencies are illustrated in Figure 8 and Figure 9. Further, the changes in the mechanics of the skating stride will then result in an increase (- sign) in stride length and propulsive time with each successive stride.

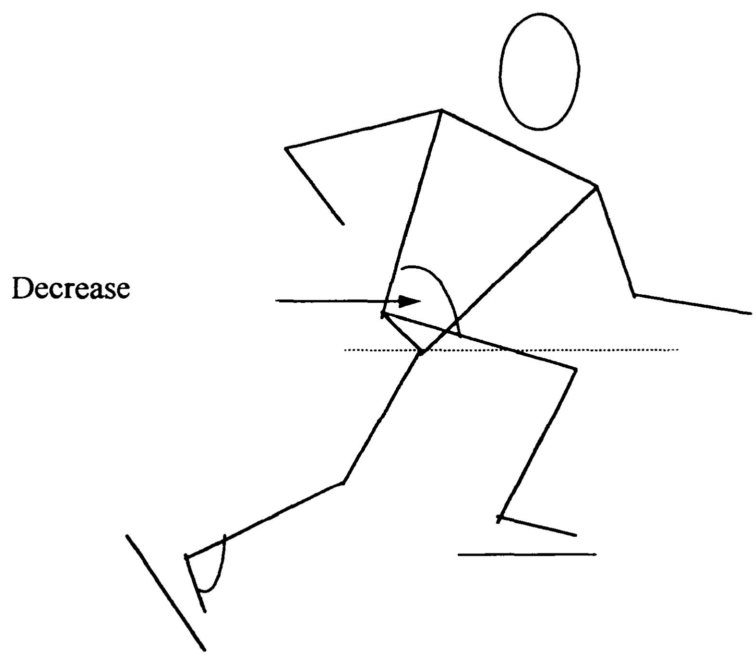

Figure 8: Tendency of kinematic variables loaded on the first latent variable (saggital view)

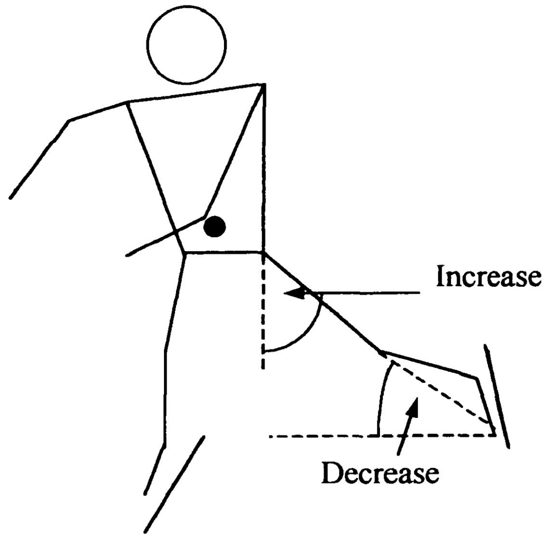

Figure 9: Tendency of kinematic variables loaded on the first latent variable (frontal view)

Factor loadings for the second latent variable highlighted the importance of the first push-off to the overall acceleration. Although hip angle at push-off and toe to center of mass at touchdown for the fifth stride exhibited strong factor loadings in this latent variable, these isolated variables were identified as inconsistent with the remaining factor loadings. The group of remaining variables, hip angle at push-off, knee angle at push-off and ankle angle at push-off in the first stride represented the summation of propulsive forces at push-off. Marino & Weese (1979) previously reported that the summation of propulsive forces in the driving leg included full extension of the knee, hyperextension of the hip and plantar flexion of the ankle at push-off. Given that the factor loadings for these variables were for the first stride, the second latent variable indicated the importance of the first push-off to overall performance and was therefore referred to as the *critical push-off factor*. Players should attempt to maximize (+ sign) their hip angle, knee angle and ankle angle at push-off in order to optimize the propulsive phase in the critical first stride and minimize the time taken to skate a given distance. These tendencies are illustrated in Figure 10.

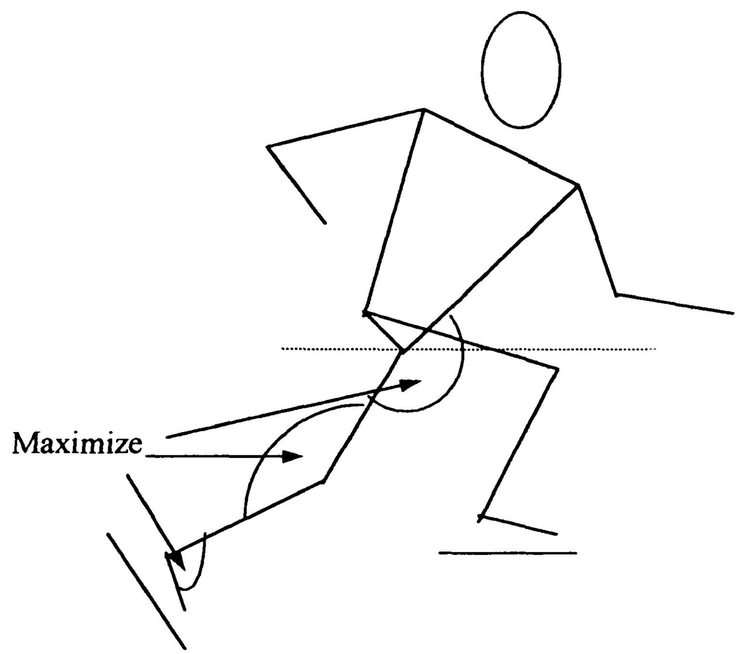

Figure 10: Tendency of kinematic variables loaded on the second latent variable.

Finally, the third latent variable included three variables with factor loadings of greater than .60, which included knee angle at touchdown for strides two and three and take-off angle for the first stride. However, take-off angle was previously identified as an important kinematic measure in the propulsion efficiency factor, and therefore the factor loading for the first stride was inconsistent with the skating characteristic identified by this latent variable. The two remaining factor loadings for knee angle at touchdown on strides two and three indicated the importance of flexion at the knees to allow for a larger range of motion during propulsion. De Koning et al. (1995) reported that in speed skating, larger ranges of motion in hip and knee joints resulted in larger extension velocities in both the X and Y-directions. Similarly, Pagé (1976) reported that the range of knee extension in ice hockey was significantly correlated to skating speed. This factor was referred to as the *propulsion preparation factor*, given that the factor loadings highlighted the importance of flexion at the knees prior to the initiation of propulsion (see Figure 11). Therefore, by maximally flexing (+ sign) the knee at touchdown, players can increase the duration in which propulsion can occur, and ultimately increase their potential skating speed.

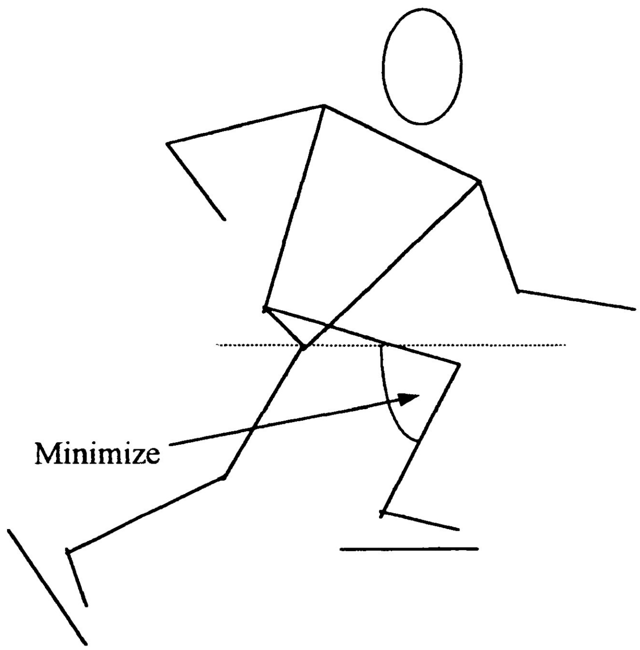

Figure 11: Tendency of kinematic variables loaded on the third latent variable.

In summary, the PCA results revealed that for optimal skating performance, players must: maximize their push-off during the first stride, prepare for propulsion with knees fully flexed at touchdown and most importantly maintain an efficient body position throughout acceleration to maximize propulsion.

Prediction of Skating Time

Nine variables were found to predict 95.3% of the variance in the time taken to skate six meters in the present study. These variables, in order of their predictive power, included:

1) transpose variable – stride length (stride 1-3)
2) toe-to-center of mass distance at touchdown (stride 3)
3) hip angle at push-off (stride 1)
4) transpose variable – propulsive time (stride 2-4)
5) player height
6) knee angle at push-off (stride 1)
7) transpose variable – hip abduction at push-off (stride 4,5)
8) hip abduction at push-off (stride 2)
9) peak anaerobic power – normalized

The results of the regression analysis in the present study differs from previous findings by Marino & Dillman (1976) and Marino (1983), in both the number of predictors and predictive accuracy of the regression equation for the time to skate six meters. Using multiple regression analysis with a forward stepwise approach, Marino & Dillman (1976) reported that four variables, forward lean angle at touchdown, take-off angle, stride rate and height, accounted for 49% of the variance in the time taken to skate six meters. Two of the four variables reported by Marino & Dillman (1976), stride rate (measured as propulsive time in this study) and player height, were significant predictors of the time to skate 6.0 m in the present study. Although the remaining two predictors identified by Marino & Dillman (1976), forward lean at touchdown (as measured by hip angle at touchdown in this study) and take-off angle were highlighted by the

PCA as important skating characteristics, these variables were not significant predictors of the time taken to skate six meters in the present study.

Previous research findings indicate that the remaining variables of the regression equation presented in this research study were also likely to influence skating performance. Specifically, stride length was a significant predictor in the present study, and was reported previously by Marino (1984) to be correlated ($r = .76$) to forward skating velocity. Likewise, toe-hip distance at touchdown was found to be a significant predictor of average acceleration by Marino & Dillman (1976). Marino & Dillman (1976) reported that leg length, a function of player height (shown in the present study), was also a significant predictor of average acceleration over six meters. Pagé (1976) and de Koning et al. (1995) suggested that the range of knee extension is related to skating velocity, while Marino & Weese (1979) described the importance of the summation of force (including knee extension) at push-off to propulsion. Although no research studies to date have examined hip abduction in ice hockey, it has been shown in the present study and in previous research that increased hip abduction is required during acceleration to maintain an effective propulsive action during skating (de Koning et al., 1995).

Finally, the inclusion of peak anaerobic power in the regression model of the present study confirms previous research by Allinger & Van den Bogert (1997), who reported that skating speed in speed skating could be limited by instantaneous power. Although peak anaerobic power had the least predictive power of all variables in the regression equation, it is apparent that this measure is related to skating performance and therefore can be used by coaches, trainers or players as an indicator of skating potential over short distances. Further, it is proposed that an improvement in peak anaerobic power, will result in a concomitant decrease in the time taken to skate six meters, provided that skating technique remains constant.

Variability of Skating Technique

The estimates of skewness and kurtosis support the homogeneity of variance in those kinematic variables that best predict the time taken to skate six meters. In this research study, little difference was observed between individuals on all of the kinematic variables included in the regression equation for the time taken to skate six meters, with the exception of the transposed variable for hip abduction at push-off. However, the estimates of skewness and kurtosis revealed an increased heterogeneity of variance in both stride characteristics included in the final regression equation, stride length and propulsion time. It is important to note that while skating technique can be learned and reinforced through coaching and practice, the variables stride length and propulsion time are more likely a function of limb length and anaerobic power (Allinger & Van den Bogert, 1997). Therefore any comparison of variance estimates on these two stride characteristics will be directly proportional to the anatomical and physiological differences between subjects.

In 1997, Allinger & Van den Bogert reported that as skating speed increased, the range of skating techniques that could be used to achieve a given skating speed decreased. Although Allinger & Van den Bogert (1997) used a simulation model for steady state speed skating, their research findings support the homogeneity of variance in skating technique used by ice hockey players during acceleration observed in the present study.

Conclusions

The results of this research study have contributed substantially to our understanding of the biomechanics of ice hockey skating technique and the prediction of on-ice acceleration. The use of three-dimensional pan and tilt video-analysis in this study has allowed for a more precise analysis of the kinematics of hockey skating technique during on-ice acceleration. Exploratory factor analyses were used to filter the set of kinematic variables by eliminating confounding kinematic variables and variables exhibiting multicollinearity. Moreover, the factor analyses identified and quantified the relationship between kinematic measures that together described important characteristics of ice hockey skating technique. The structural relationships highlighted the importance of progression throughout acceleration for some kinematic variables as well as the importance of individual strides for other kinematic measures.

The use of the log-log transformation of the power function to transpose raw scores within a variable set into a single composite score has captured the progressive nature of the skating stride without masking the unique contribution of each individual stride. The inclusion of peak anaerobic power in the multiple regression model confirmed Allinger & Van den Bogert's (1997) theory that instantaneous power can limit skating performance in skating sports. Further, the inclusion of peak anaerobic power in the regression model demonstrates the importance of combining physiological and biomechanical measures in an attempt to accurately describe or predict sport performance. Finally, it is important to recognize that in this study the analysis of the skewness and kurtosis estimates for predictors of skating performance identify the homogeneity of variability in ice hockey skating technique, while also illustrating the heterogeneity in stride characteristics within the elite level ice hockey players sampled in this study.

Recommendations

The following recommendations are offered for future research:

1) Similar methodologies should be used to validate the kinematics of forward skating at steady state skating speeds as well as a combination of acceleration and steady state skating.
2) These results of the present should be validated for a variety of levels of skating ability and over a range of age groups.
3) Three-dimensional video analysis should be used to analyze and evaluate various other skating movements commonly performed in the sport of ice hockey, including, cross-overs, agility movements and stop-start actions.
4) Further analysis of the action of the upper body during acceleration and its contribution to skating performance.

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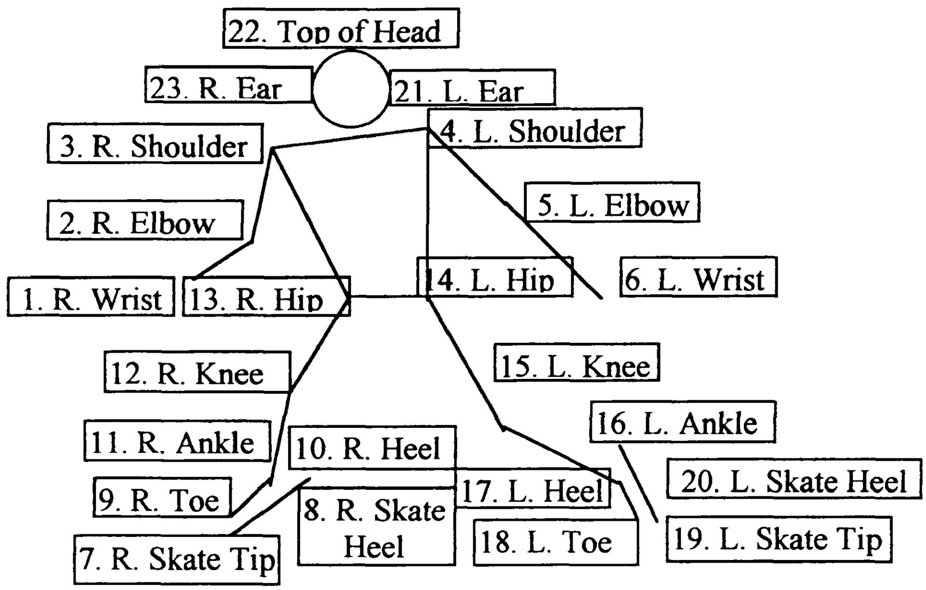
Appendix A: Spatial Model



Appendix B: Kinematic Variables of Interest

Name of Variable	Description	Abbr.
Hip Angle	Angle between the trunk and thigh of push-off side	H_P*i*
Hip Angle	Angle between the trunk and thigh of touchdown side	H_T*i*
Lean Angle	Angle between the trunk and horizontal of push-off side	LPO_*i*
Lean Angle	Angle between the trunk and horizontal of touchdown side	LTD_*i*
Knee Angle	Angle between the thigh and shank at push-off	K_P*i*
Knee Angle	Angle between the thigh and shank at touchdown	K_T*i*
Ankle Angle	Angle between the foot and shank at push-off	A_*i*
Skate-V Angle	Angle between the skate blade of left and right skate blades at touchdown	SKTV_*i*
Propulsive Angle	Angle between the skate blade and the direction of travel at push-off	PA_*i*
Take-off Angle	Angle above the horizontal of a line from the toe of the boot to the hip at push-off	TO_P*i*
Hip Abduction Angle	Angle between the thigh and the vertical plane at push-off	HABD_*i*
Shoulder Flexion	Angle between the humerus and the XY plane (positive Z-coordinate)	SHFL_*i*
Shoulder Extension	Angle between the humerus and the XY plane (negative Z-coordinate)	SHE_*i*
Shoulder Abduction	Angle between the humerus and the YZ plane (positive X-coordinate)	SHAB_*i*
Shoulder Adduction	Angle between the humerus and the YZ plane (negative X-coordinate	SHAD_*i*
Stride Rate	The number of strides per second	SR_*i*
Stride Length	The horizontal distance in the Z-direction from push-off of one leg to push-off of the other	SL_*i*
Propulsion Time	The time taken from touchdown of skate to push-off of same skate	PT_*i*
Double Support Time	The time during which both skates are in contact with the ice during a stride	DST_*i*
Height of Center of Mass	The height above the right skate tip at touchdown of the right leg	HCM_*i*
Vertical Displ. of Foot	The maximum vertical displacement of the left foot during the recovery phase	FVD_*i*

Appendix C: Joint, Segment and Segment-Plane Angles

Angle	Endpoint 1	Vertex	Endpoint 2
Left Hip	4	14	15
Left Knee	16	15	14
Left Ankle	15	16	18
Right Hip	3	13	12
Right Knee	11	12	13
Right Ankle	12	11	9

Angle	Endpoint A1	Endpoint A2	Endpoint B1	Endpoint B3
Skate-V	7	8	20	19

Angle	Endpoint A1	Endpoint A2	Plane
Right Propulsive	7	8	YZ
Left Propulsive	20	19	YZ
Right Hip Abduction	12	13	YZ
Left Hip Abduction	15	14	YZ
Right Shoulder Abduction/Adduction	2	3	YZ
Left Shoulder Abduction/Adduction	5	4	YZ
Right Hip Flexion/Extension	12	13	XY
Left Hip Flexion/Extension	15	14	XY
Right Shoulder Flexion/Extension	2	3	XY
Left Shoulder Flexion/Extension	5	4	XY
Right Take-off	13	7	XZ
Left Take-off	14	20	XZ
Right Torso Lean	3	13	XZ
Left Torso Lean	4	14	XZ

Appendix D: Descriptive Statistics for Raw Kinematic Data

Variable	N	Mean	Std. Dev.	Min.	Max.	Skew.	Kurt.
H_T1	21	100.79	10.63	75.71	117.91	-0.526	0.102
H_T2	21	102.77	10.89	71.72	117.27	-0.970	1.847
H_T3	21	90.29	9.19	66.13	106.35	-0.803	1.239
H_T4	21	96.17	8.85	68.04	110.50	-1.411	4.213
H_T5	21	81.28	9.00	58.06	93.88	-1.098	1.267
H_P1	21	159.35	13.13	124.30	176.20	-1.052	1.401
H_P2	21	148.52	9.16	133.69	164.21	0.133	-1.021
H_P3	21	150.68	7.29	134.89	164.59	-0.423	0.781
H_P4	21	139.84	6.12	125.97	148.86	-0.872	0.467
H_P5	21	142.96	9.85	124.51	158.37	-0.343	-0.885
K_T1	21	107.25	5.22	95.50	118.03	-0.332	0.568
K_T2	21	106.74	4.96	97.46	117.94	0.286	-0.171
K_T3	21	101.03	5.66	87.89	109.39	-0.951	1.112
K_T4	21	103.13	3.95	96.47	111.49	0.269	0.153
K_T5	21	97.21	4.60	87.32	105.90	-0.044	-0.084
K_P1	21	158.05	8.70	131.90	169.30	-1.195	2.860
K_P2	21	155.78	6.13	146.65	169.87	0.400	0.052
K_P3	21	158.18	6.24	147.78	169.38	-0.072	-1.133
K_P4	21	155.34	5.46	144.16	166.03	-0.040	0.231
K_P5	21	156.89	5.26	146.62	166.40	-0.020	-0.635
A_P1	21	117.09	7.47	102.78	128.26	-0.419	-0.399
A_P2	21	118.18	6.68	106.73	131.53	0.741	-0.008
A_P3	21	117.72	3.66	112.18	123.76	0.158	-1.017
A_P4	21	115.52	7.29	105.55	133.49	0.910	0.450
A_P5	21	116.22	5.89	100.22	125.74	-0.803	1.302
SKTV_1	21	108.51	14.08	77.64	141.12	0.056	0.620
SKTV_2	21	88.63	11.12	57.91	106.93	-0.760	1.844
SKTV_3	21	89.97	8.82	66.39	103.84	-0.599	1.160
SKTV_4	21	75.79	10.19	56.37	94.76	-0.432	-0.168
SKTV_5	21	77.02	8.78	62.34	93.04	0.052	-0.883
PA_1	21	65.44	9.57	48.70	79.63	-0.334	-1.357
PA_2	21	55.37	6.28	37.95	69.61	-0.502	2.538
PA_3	21	59.25	9.15	43.09	72.89	-0.224	-1.213
PA_4	21	52.04	4.18	46.18	59.82	0.193	-1.064
PA_5	21	53.88	7.69	36.53	66.00	-0.491	-0.136
HABD_P1	21	5.93	3.43	0.39	13.06	0.298	-0.222
HABD_P2	21	12.15	6.59	1.40	26.62	0.142	-0.288
HABD_P3	21	8.13	6.83	0.05	24.26	0.913	0.517
HABD_P4	21	19.75	3.78	12.74	27.36	0.281	-0.246
HABD_P5	21	16.75	3.78	7.75	28.05	0.612	-0.554

Variable	N	Mean	Std. Dev.	Min.	Max.	Skew.	Kurt.
HF_T1	21	38.17	6.68	25.49	48.96	-0.501	-0.707
HF_T2	21	41.32	5.45	32.36	52.31	0.338	-0.311
HF_T3	21	48.81	5.94	37.99	59.75	-0.046	-0.280
HF_T4	21	47.61	4.06	38.33	55.34	-0.058	0.157
HF_T5	21	55.09	4.61	45.98	63.56	0.008	-0.222
HE_P1	21	26.17	7.66	1.97	37.42	-1.390	4.011
HE_P2	21	24.27	5.09	15.26	38.95	0.977	2.455
HE_P3	21	25.35	4.78	18.74	35.84	0.507	-0.423
HE_P4	21	22.11	4.20	11.08	30.26	-0.529	1.192
HE_P5	21	22.70	5.21	10.32	32.18	-0.433	0.519
SHE_P1	21	44.10	12.74	24.94	70.39	0.361	-0.591
SHF_P1	21	-4.22	16.25	-30.92	36.38	0.533	0.323
SHE_P2	21	45.53	14.93	16.36	70.04	0.033	-0.689
SHF_P2	21	3.42	12.56	-25.50	23.48	-0.274	-0.076
SHE_P3	21	44.09	11.58	20.24	68.49	-0.127	0.125
SHF_P3	21	-0.51	13.16	-21.72	31.63	0.572	0.354
SHE_P4	21	43.32	11.20	17.75	66.43	0.043	0.272
SHF_P4	21	2.89	12.86	-27.21	26.17	-0.640	0.351
SHE_P5	21	44.42	13.39	12.80	73.75	-0.361	1.008
SHF_P5	21	-1.02	9.39	-14.61	25.29	0.974	2.148
SHAB_P1	21	42.79	11.46	15.15	60.58	-0.654	0.158
SHAD_P1	21	20.12	14.77	0.60	47.83	0.208	-1.097
SHAB_P2	21	40.57	12.66	17.31	57.02	-0.551	-0.924
SHAD_P2	21	14.13	17.34	-5.78	55.15	0.960	0.209
SHAB_P3	21	41.56	14.17	3.50	69.41	-0.675	1.719
SHAD_P3	21	8.52	9.97	-4.01	31.99	0.799	0.278
SHAB_P4	21	44.72	10.84	23.22	65.87	-0.196	-0.533
SHAD_P4	21	2.57	10.87	-16.46	33.32	1.057	2.138
SHAB_P5	21	42.63	14.51	13.75	77.07	0.355	0.479
SHAD_P5	21	1.85	12.36	-17.62	29.28	0.782	-0.196
FVD_2	21	0.195	0.06	0.10	0.33	0.656	0.045
FVD_4	21	0.193	0.05	0.10	0.30	0.013	-0.195
FVD_6	21	0.193	0.06	0.11	0.30	0.397	-0.867
TO_P1	21	53.23	4.62	46.88	67.27	1.232	3.190
TO_P2	21	53.83	2.76	47.74	58.55	-0.413	0.018
TO_P3	21	52.57	2.82	47.39	56.49	-0.350	-0.956
TO_P4	21	52.02	2.62	44.92	56.34	-0.940	1.666
TO_P5	21	50.30	2.91	44.02	54.90	-0.232	-0.322
SL_1	21	1.02	0.27	0.29	1.45	-0.736	1.086
SL_2	21	1.18	0.18	0.84	1.57	0.607	0.858
SL_3	21	1.47	0.19	1.15	1.76	0.007	-1.251
SL_4	21	1.61	0.18	1.23	2.00	-0.086	0.572
SL_5	21	1.85	0.24	1.42	2.19	-0.487	-1.032

Variable	N	Mean	Std. Dev.	Min.	Max.	Skew.	Kurt.
SR_1	21	3.74	0.27	3.16	4.29	-0.259	0.213
SR_2	21	3.80	0.34	3.16	4.29	-0.017	-1.087
SR_3	21	3.71	0.24	3.33	4.00	-0.333	-1.068
SR_4	21	3.76	0.28	3.33	4.29	0.201	-0.550
SR_5	21	3.47	0.29	3.00	4.00	0.022	-1.122
PT_1	21	0.245	0.03	0.18	0.30	-0.173	0.035
PT_2	21	0.248	0.02	0.22	0.30	0.368	-0.677
PT_3	21	0.265	0.02	0.23	0.30	-0.135	-0.828
PT_4	21	0.267	0.03	0.22	0.32	-0.190	0.143
PT_5	21	0.295	0.03	0.25	0.33	-0.202	-1.372
DST_1	21	-0.024	0.016	-0.083	0.000	-2.522	8.873
DST_2	21	-0.018	0.022	-0.083	0.017	-1.053	2.908
DST_3	21	-0.006	0.015	-0.050	0.017	-1.421	2.867
DST_4	21	0.001	0.013	-0.017	0.033	0.727	0.699
DST_5	21	0.004	0.011	-0.017	0.033	0.914	1.514
HCM_T1	21	0.91	0.06	0.78	1.00	-0.236	-0.241
HCM_T3	21	0.90	0.06	0.77	0.98	-0.680	-0.131
HCM_T5	21	0.87	0.05	0.75	0.94	-0.647	-0.050
TCD_T1	21	-0.026	0.09	-0.20	0.24	0.757	1.389
TCD_T2	21	-0.086	0.06	-0.18	0.04	0.378	-0.302
TCD_T3	21	-0.150	0.06	-0.26	0.03	1.134	3.007
TCD_T4	21	-0.155	0.03	-0.20	-0.08	0.831	0.437
TCD_T5	21	-0.174	0.05	-0.24	-0.09	0.136	-0879
LTD_1	21	52.34	6.98	34.49	63.07	-0.654	0.860
LTD_2	21	54.04	7.55	33.38	66.04	-0.869	1.670
LTD_3	21	49.71	5.71	34.27	58.26	-0.892	1.421
LTD_4	21	53.69	6.71	33.07	63.73	-1.202	3.514
LTD_5	21	46.56	6.96	30.48	56.24	-1.183	0.914
LPO_1	21	43.31	8.67	28.79	58.64	0.028	-0.601
LPO_2	21	35.62	7.70	23.06	52.10	0.041	-0.296
LPO_3	21	36.99	6.77	21.93	49.23	-0.338	0.200
LPO_4	21	31.15	5.96	16.03	41.86	-0.864	1.234
LPO_5	21	32.95	6.33	20.05	42.93	-0.429	-0.725