Aerobic Capacity Is Associated With Improved Repeated Shift Performance in Hockey

Benjamin J. Peterson, John S. Fitzgerald, Calvin C. Dietz, Kevin S. Ziegler, Stacy J. Ingraham, Sarah E. Baker, and Eric M. Snyder

School of Kinesiology, University of Minnesota, Minneapolis, Minnesota; and Department of Kinesiology and Public Health Education, University of North Dakota, Grand Forks, North Dakota

Abstract

Peterson, BJ, Fitzgerald, JS, Dietz, CC, Ziegler, KS, Ingraham, SJ, Baker, SE, and Snyder, EM. Aerobic capacity is associated with improved repeated shift performance in hockey. J Strength Cond Res 29(6): 1465–1472, 2015—Current research has found conflicting results regarding the relationship between maximal oxygen uptake (VO2peak) and the repeated sprint ability (RSA) of hockey players. The purpose of this study was to use sport-specific testing methods to investigate this relationship. Forty-five (range, 18–24) college hockey players completed a graded exercise test on a skating treadmill to ascertain their VO2peak. An on-ice repeated shift test was then conducted to evaluate each player’s susceptibility to fatigue. First gate, second gate, and total test times were collected on the course and then used to calculate associated decrement scores. Second gate decrement was significantly correlated to VO2peak (r = -0.31, p = 0.04). Final stage completed during the graded exercise test was also significantly correlated to second gate and total decrement (r = -0.46, p = 0.001; r = -0.32, p = 0.03). No significant correlation was found between either first gate or total decrement score and VO2peak (r = -0.11, p = 0.46; r = -0.17, p = 0.26). The results of this study indicate that RSA is associated with VO2peak and final stage completed when using sport-specific testing methods.

Key Words fatigue, skating, recovery, intervals, specificity, anaerobic

Introduction

Sport-specific training has been shown to improve performance in repeated sprint sport athletes (i.e., soccer, football, rugby, basketball, and ice hockey). Success in repeated sprint sports is largely dictated by a player’s ability to produce power; the player that is quicker to the ball or faster off the line will often beat their opponent; giving them an advantage. Competitions for these sports, however, take place over the period of several hours and are divided into quarters, halves, or periods; each of these consisting of numerous maximal-work bouts interspersed with relatively short recovery periods (28). The ability to repeatedly produce high-power outputs throughout a competition gives a competitive edge to a player over his/her opponent and is an important fitness component in repeated sprint sports (19). This ability has come to be known as repeated sprint ability (RSA).

In the repeated sprint sports of rugby and soccer, VO2peak has been shown to correlate with RSA, ranging from \( r = -0.50 \) to \(-0.83 \) (7,37). This relationship is further supported by research showing that a state of hypoxia can impair RSA in athletes (3,32). In addition, creating a hyperoxic environment seems to improve RSA through increased aerobic adenosine triphosphate (ATP) contribution and phosphocreatine (PCr) resynthesis rate (3). This evidence suggests that aerobic capacity and improved oxygen utilization may affect RSA by (a) increasing the rate of the fast and slow phase of PCr resynthesis (26), (b) enhancing the clearance rate of metabolites created by PCr breakdown and glycolysis (8,40), (c) improving oxygen (VO2) kinetics (14), and (d) increasing aerobic energy contribution during maximal sprint bouts (37).

Disagreement exists regarding the strength of this association, as there is research to refute these findings. Numerous researchers have failed to find a significant association \((-0.35 < r < -0.46)\) between VO2peak and RSA in rugby and soccer athletes (1,8,12,39), but it is not clear what role sample size \((n < 15)\) played in calculating these statistics. The discrepancy in the research would advocate for additional studies to be conducted to better understand the possible relationship between aerobic capacity and RSA.

Adding to these conflicting findings, there is very little published on the sport of ice hockey and RSA. The current hockey RSA research has a large deficiency in that the researchers used a modified Bruce protocol on a motor-driven treadmill to ascertain VO2peak (12). This testing modality has been found to have no correlation between the on-ice and off-ice VO2peak values in collegiate hockey players (15). Taking these findings into account, it is possible that the lack of a correlation in the current research could be due to poor
testing protocol selection. In addition, the majority of RSA tests use protocols that only use straight ahead running or skating (12,16). This can be problematic when interpreting direct correlations to performance, as athletes move in a 360° plane of motion during competition (18). Researchers have found that athletes completing a course with multiple changes in direction placed a greater energy demand on their metabolic systems when compared to straight ahead running covering the same distance (33). This would indicate that RSA tests using only straight ahead running do not simulate the stress placed on an athlete during competition. Consequently, there is a need for a study to look at the role aerobic capacity plays on RSA in hockey players, using a protocol that accounts for both the task specificity of skating and the movement patterns performed in competition.

This study aims to address the current limitations specific to ice hockey and RSA in 3 ways: (a) address a current population-specific void in ice hockey RSA research, (b) account for task specificity by obtaining players' Vo2peak on a skating treadmill using a graded exercise test, and (c) evaluate RSA using an on-ice test that mimics the motor patterns typically performed by ice hockey players during competition. The results of this study could have important implications for the training methods used to prepare ice hockey players for their competitive season. Therefore, the purpose of this study will be to investigate the relationship between Vo2peak and RSA in hockey players. It is hypothesized that hockey players with a higher aerobic Vo2peak or higher number of stages completed during a skating graded exercises test will exhibit less fatigue during an on-ice repeated shift test than those with lower values.

METHODS

Experimental Approach to the Problem
Participants signed up for 3 testing sessions: (a) physical characteristics, (b) aerobic capacity, and (c) on-ice repeated shift test. Each session took approximately 1 hour and was held on the University of Minnesota campus. All participants were tested in early June, at the start of their summer training schedules, with all 3 sessions completed within a 10-day period, ensuring at least 2 days rest between sessions. Participants were told before each session to refrain from heavy exercise 24 hours before their testing sessions. All participants were told to eat a light meal and hydrate 2 hours before their testing session. In addition, they were asked to refrain from caffeine, tobacco, and alcohol 12 hours before testing. Aside from these guidelines, participants were asked to maintain a normal diet and exercise regimen during testing. Exclusion criteria for the study included absence from on-ice skating over the previous 30 days due to prior or current injury and players self-reporting their position of goaltender.

Subjects
Forty-five male hockey players, aged 18–24 years and playing Division I, Division III, or Elite Junior level hockey in the Minneapolis, MN area, volunteered for this study. All testing procedures were approved by the Institutional Review Board at the University of Minnesota before participant recruitment and data collection. Written informed consent was obtained from all participants before the start of the study.

Procedures

Session 1: Determination of Physical Characteristics. Session 1 took place in the Laboratory of Physical Hygiene and Exercise Science (LPHES). It consisted of anthropometric, vertical jump, Wingate, and grip strength testing. Participants were instructed to wear team-issued workout gear (e.g., shorts, compression shorts, t-shirt) to the LPHES. Researchers started by recording the standing height and weight of each participant. Standing height was recorded using the Frankfort Plane criterion (22) and weight using a Detecto Mechanical Doctor's scale (Model #439, Webb City, MO, USA). Participants were asked to remove their clothing, except for a pair of spandex compression shorts, to record their weight.

Body composition was assessed through hydrostatic weighing using ExerTech Body Densitometry Systems software (Dresbach, MN, USA). The method is considered to be a valid and reliable method for measurement of body composition (22). Participants were asked to enter the tank and run their hands all over their body to try to remove as many air bubbles as possible from their skin, hair, and compression shorts. The participants would then submerge and exhale as much air from their lungs as possible, signaled by the cessation of bubbles coming from the participant’s mouth, before the measure was recorded. The participant’s weight was recorded 8 times to account for both a learning effect, as well as to ensure consistency of the measure and accuracy of the reported weight (22). The heaviest duplicated weight was recorded as the participant’s underwater weight. If the participants were unable to duplicate either their first or second heaviest weight, their third heaviest weight was recorded as the official underwater weight. Percent body fat was calculated using the Brozek equation (22). Residual lung volume was also calculated (25). This method has been deemed an acceptable alternative when direct measurement is unfeasible (22).

Session 2: Determination of Aerobic Capacity. Aerobic capacity was assessed on both a Frappier (Accelaration, Minneapolis, MN, USA, n = 30) and The Blade (Woodway, Waukesha, WI, USA, n = 15) skating treadmills to ascertain the Vo2peak of each participant. Breath-by-breath analysis was performed by an Ultima CPX (Medgraphics, St. Paul, MN, USA). The skating treadmill protocol used has been previously validated as a reliable means for participants to reach volitional exhaustion accurately and precisely measure Vo2peak (24). The protocol began with participants skating at a speed of 6.5 miles per hour (mph) and a 2% grade. Every minute, the speed of the treadmill was increased 0.5 mph until a maximal speed of 10 mph was reached; this occurred 8 minutes into the test.
Once the participants had reached maximal speed, the grade was increased by 1% every minute until they reached volitional exhaustion. Criteria for reaching maximal aerobic capacity was determined by achieving 2 of the 3 following criteria: (a) maximal heart rate \((220 - \text{age} \pm 10)\), (b) RER value >1.10, and (c) rate of perceived exertion >18 (6).

**Session 3: On-Ice Repeated Shift Test.** Session 3 took place at the hockey arena and consisted of the on-ice repeated shift test. To our knowledge, there is no precedence in the literature for an on-ice repeated shift test. Although articles have been published using on-ice repeated sprint tests to evaluate performance, these tests do not mimic the physical demands encountered by players during competition (12). In addition, it has been shown that off-ice tests do not predict the on-ice performance of hockey players (38). To address this shortfall, an on-ice repeated shift test was created for this study that mimics the intensity, duration, and movement patterns performed by a hockey player during a shift to evaluate the participant’s susceptibility to fatigue during maximal intensity skating.

To create the test, data were collected from the National Hockey League (NHL) database concerning the shift length, number of shifts played per period, and rest intervals between shifts by forwards in the NHL from 2009 to 2011. It was found the average shift length by an NHL forward to be 45.5 ± 3.9 seconds, with average shifts completed per period calculated at 6.8 ± 1.1, and a rest interval of 73.4 ± 16.6 seconds (excluding power plays). Other research has estimated that hockey players spend approximately 50% of their time on the ice in some form of high-intensity activity (sprinting, striding, skirmishing, etc.) (28). When this percentage is applied to the calculated parameters of a hockey shift, it can be inferred that a hockey player will spend approximately 22.7 seconds of a shift in a maximal, or near-maximal, skating state.

When the participants arrived at the rink, they were told to change into full gear and go out on the ice. Two skaters were tested at the same time, alternating back and forth between testing bouts, with the ice being resurfaced after every sixth skater. Participants were instructed to have their skates sharpened to game specifications before testing. When the participants stepped onto the ice, they were told to go through their typical pregame warm-up. When the participants said they were ready, they joined the researchers at the starting line. The participants were told the basic parameters of the test. In addition, they were told the 2 goals of the test: (a) skate the course as fast as possible and (b) have the lowest drop-off in time from your best course time as possible to dissuade them from pacing the course.

The participants then watched an instructor glide through the course to understand its layout. Each participant was then asked to skate the course at 50% of his best effort to gain familiarization. On completion of the familiarization trial, each participant was asked if he felt comfortable with the course. If he said, “no,” he was instructed to skate the course 1 additional time. The participants were given 3 minutes to rest after the familiarization trial to ensure they were fully recovered before commencement of testing.

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**Figure 1.** The on-ice repeated shift test consists of 8 maximal skating bouts, with 90 seconds of passive recovery between bouts. The skater starts with their skate at the face-off line; stick behind the laser timer. When given the “start” command, the skater sprints to the blue line, making a hard cut, pushing off their left leg (post leg), and sprinting to the far side of the goalie crease. The skater then makes a hard cut, pushing off their right leg (post leg), and sprints the length of the ice. The skater makes hard crossover steps to their left, going around the circle. After reaching the top of the circle, the skater sprints to the base of the right circle, making hard crossover steps to their right. When the skater had completed the turn, they sprinted along the boards through the red line (finish line).
The test itself consisted of 8 maximal skating bouts, performed in full gear (including their stick), lasting approximately 22.7 seconds with 90 seconds of passive recovery between bouts. The course protocol can be seen in Figure 1. Course times were measured by a TC Speed Trap-II wireless timing system (E38720; Gill Athletics, Champaign, IL, USA). There were 3 separate timing gates, used to evaluate first half, second half, and total fatigue decrement. Fatigue was calculated as a percent decrement score (% Decrement Score = \( \frac{100 \times (\text{Total Sprint Time} - \text{Ideal Sprint Time})}{\text{Total Sprint Time}} \) (20).

The 90-second recovery time started immediately after the participants crossed the finish line. Participants were told that during their recovery time, they could stand, take a knee, or lay on the ice; they could not skate around. The participants were informed when they had 30 seconds and 10 seconds of rest time remaining, with a 5-second countdown to the start. This sequence was completed 8 times, with times being recorded after each sprint bout. Participants were not allowed to drink any sports drinks or mixes during testing; however, water was provided without restriction to the participants. It should be noted that the test-retest reliability of this test has not been established; however, its basic structure is congruent with other validated RSA tests.

**Statistical Analyses**

This cross-sectional study is powered for a 2-sided test with an effect size of 0.5 and a power of 0.80. The sample size required to show significance within these parameters was calculated to be \( n = 36 \) (23). Mean and SDs were calculated for all variables. Analysis of \( \dot{V}_O_2 \) peak data was performed by the Breezesuite software package (Medgraphics, St. Paul, MN). Statistical analysis of the collated data was performed

**TABLE 1.** Descriptive characteristics of subjects.*

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample size (n)</td>
<td>45</td>
</tr>
<tr>
<td>Age (y)</td>
<td>20 ± 2.0</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>181 ± 9.0</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>84 ± 12.0</td>
</tr>
<tr>
<td>Body fat (%)</td>
<td>12.5 ± 4.0</td>
</tr>
<tr>
<td>Relative ( \dot{V}_O_2 ) peak (ml·kg(^{-1}·)min(^{-1}))</td>
<td>54.9 ± 4.4</td>
</tr>
<tr>
<td>Absolute ( \dot{V}_O_2 ) peak (ml·min(^{-1}))</td>
<td>4649 ± 415</td>
</tr>
<tr>
<td>Final stage completed (treadmill test)</td>
<td>9.67 ± 2.0</td>
</tr>
</tbody>
</table>

*\( \dot{V}_O_2 \) peak = maximal oxygen consumption; final stage completed = furthest stage reached during the skating treadmill test.

**TABLE 2.** On-ice repeated shift test results.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fastest course time</td>
<td>23.02 ± 0.61</td>
</tr>
<tr>
<td>Slowest course time</td>
<td>26.47 ± 1.53</td>
</tr>
<tr>
<td>Average course time</td>
<td>25.05 ± 1.02</td>
</tr>
<tr>
<td>Average first gate time</td>
<td>9.90 ± 0.86</td>
</tr>
<tr>
<td>Average second gate time</td>
<td>15.30 ± 1.17</td>
</tr>
<tr>
<td>First gate decrement (%)</td>
<td>8.12 ± 3.47</td>
</tr>
<tr>
<td>Second gate decrement (%)</td>
<td>9.08 ± 2.95</td>
</tr>
<tr>
<td>Total course decrement (%)</td>
<td>8.90 ± 3.30</td>
</tr>
</tbody>
</table>

**Figure 2.** The relationship between \( \dot{V}_O_2 \) peak and fatigue (percentage decrement score) during the on-ice repeated shift test; broken down into (A) gate 1 fatigue, (B) gate 2 fatigue, and (C) total course fatigue. *Significant correlation between variables (\( p \leq 0.05 \)).
by SPSS software (version 21.0; IBM, Armonk, NY, USA). Data were analyzed using either a Pearson’s or Spearman’s correlation test, depending on the distribution of the data. Correlational coefficients ($r$) were used to detect associations between the independent and dependent variable. Multiple regression was used to determine the combined influence of $V_{\text{O}_2}\text{peak}$ and end stage completed during the graded exercise test on measures of fatigue while controlling for the use of 2 skating treadmills. The on-ice repeated shift test had 1 participant with a problematic point that was significantly deviated from the mean for all 3 timing gates. Because this subject’s data point was not a statistical outlier, this point was winsorized to 1 unit above the next highest data point to meet criteria for normal distribution. For all statistical tests, an alpha level of $p \leq 0.05$ was operationally defined as statistical significance.

**RESULTS**

Forty-five male hockey players participated in this study (Table 1). All participants met criteria for normalcy in each tested variable. The mean $V_{\text{O}_2}\text{peak}$ for participants was $54.9 \pm 4.4 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$. Times and decrement scores for first gate, second gate, and total are described in Table 2. Skate times continued to increase from sprint 1 to sprint 8, indicating fatigue, which was the main objective of course design. No significant correlation was found between either first gate or total decrement score and $V_{\text{O}_2}\text{peak}$ ($r = -0.11, p = 0.46; r = -0.17, p = 0.26$; Figure 2). Second gate decrement, however, was significantly correlated to $V_{\text{O}_2}\text{peak}$ ($r = -0.31, p = 0.04$; Figure 3), indicating that 9.6% of the variance in fatigue of the participants can be explained by their aerobic capacity ($V_{\text{O}_2}\text{peak}$).

Final stage completed during the graded skating treadmill test was significantly correlated to second gate and total decrement found during the on-ice repeated shift test when controlled for treadmill type ($r = -0.49, p = 0.001; r = -0.32, p = 0.03$; Figure 3). Final stage completed accounted for 21 and 10% of the variance, respectively. These correlation coefficients indicate that a larger portion of the variance in on-ice fatigue can be explained by end stage completed than $V_{\text{O}_2}\text{peak}$. There was no significant correlation between final stage completed and first gate decrement ($r = -0.21, p = 0.17$; Figure 3).

Using multiple regression analysis, final stage completed and $V_{\text{O}_2}\text{peak}$, combined, were significant predictors of second gate fatigue when accounting for the use of 2 treadmills ($r^2 = 28.7\%$, $p \leq 0.05$). Independently, final stage completed accounted for 23.0% of the variance ($p \leq 0.05$) of gate 2 fatigue, with an additional 4.2% of the model being accounted for by $V_{\text{O}_2}\text{peak}$ ($p = \text{ns}$). Final stage completed was also significantly related to total decrement ($r^2 = 16.8\%, p \leq 0.05$); however, the addition of $V_{\text{O}_2}\text{peak}$ did not improve the predictive ability of the model, as indicated by a nonsignificant $F$ value ($r^2 = 18.8\%, p = \text{ns}$).

**DISCUSSION**

There are 2 key findings of this study. First, that maximal oxygen uptake ($V_{\text{O}_2}\text{peak}$), assessed on a skating treadmill, was significantly correlated to fatigue, expressed as a decrement score, during the second half of a mock hockey shift in competitive college hockey players. This study is the first to show that this significant correlation exists in this population of athletes. Second, end stage completed during the graded exercise test was significantly correlated to second gate and total course fatigue, accounting for a greater portion of the variance than $V_{\text{O}_2}\text{peak}$, and likely
being a better predictor of on-ice performance than aerobic capacity alone. In addition, the manner in which data were collected during the on-ice repeated shift test, collected at multiple timing gates throughout the course, was unique to this study and allowed for a more thorough understanding of the physical performance and possible energy pathway contributions of hockey players during competition.

Earlier research has found $V_{O_{2}}$peak, assessed using running protocols, to be significantly correlated to RSA in field based team sports ($r = -0.50$ to $-0.83; \rho \leq 0.05; 4.7,14,26,37$). These researchers have theorized that fatigue is associated primarily with one, or a combination of, 4 intramuscular conditions; all of which are affected by oxygen availability: (a) diminished rate of PCr resynthesis, (b) slow the rate of inorganic phosphate accumulation, (c) decreased rate of glycolytic flux, and (d) increase the level of muscle acidosis. This research would imply that hockey players with higher maximal oxygen capacities would be better able to mitigate the effects of these fatigue causing factors and maintain their performance on the ice better than players with lower levels. In addition, players who are more efficient skaters would place less strain on their metabolic system while skating, limiting the accumulation or affect of fatigue causing factors. Simply put, efficient skaters do not have to work as hard as their inefficient peers and thus perform better on the ice. Despite ice hockey having similar energy demands as other team sports, these associations have not been found in hockey players. To date, there is only 1 study to have specifically tested the relationship between RSA and $V_{O_{2}}$peak in this population, which did not find a significant correlation between the variables ($r = -0.42; \rho = ns; 12$).

Earlier research conducted in the sport of ice hockey was performed with several limitations that may have hindered their ability to detect these associations; namely lack of testing specificity for $V_{O_{2}}$ determination, utilization of a sport-specific RSA test, and small sample size. This study addressed those barriers by accounting for task specificity in testing $V_{O_{2}}$peak on a skating treadmill, evaluating RSA using an on-ice test developed to mimic the movement parameters typically performed by hockey players during competition, and obtaining a sufficient sample size to detect the correlation as determined by a power analysis.

A recent study found that there was no correlation between on-ice and off-ice $V_{O_{2}}$peak values in collegiate hockey players (15). The researchers concluded that running $V_{O_{2}}$peak was not an adequate predictor of on-ice $V_{O_{2}}$peak and suggested that hockey players be tested in a sport-specific manner to garner reliable results. Studies performed before 2007 have only used a modified Bruce protocol on a motor-driven treadmill to ascertain maximal oxygen capacity (12). Taking these findings into account, it is possible that the lack of an association in the earlier research was due to testing protocol selection and specificity of task. This study is the first to compare a sport-specific skating $V_{O_{2}}$peak testing protocol to an RSA test in ice hockey.

Most RSA tests use protocols that only use linear movement (12,16). This can be problematic when interpreting direct correlations to performance, as athletes move in a 360° plane of motion during competition (18). Athletes completing a course with multiple changes in direction, when compared to straight ahead running, covering the same distance, place a greater energy demand on their metabolic system (33). This would indicate that RSA tests using only linear movement might not adequately simulate the stress placed on an athlete during competition. This study addressed this deficiency by creating an on-ice shift test that mimicked the movement patterns a hockey player would regularly perform during competition.

In addition, the parameters of an RSA test may heavily influence the relationship between fatigue and $V_{O_{2}}$peak. The results of an RSA test can vary greatly between studies due to the fact that there is not a “gold-standard” RSA testing protocol. The rate of fatigue can be influenced by the number of sprint bouts, the duration of the bouts, or the recovery period between bouts. The recovery period can further be examined in terms of total time, intensity, and mode (active or passive), having a significant effect on a studies results (5,11,13,35). Therefore, a primary goal of this study was to create an on-ice skating test that mimicked the intensity, skating time, movement patterns, and recovery that a hockey player would be subject to during a hockey shift. Careful consideration was given to the design and layout of the on-ice repeated sprint course used in this study. Each aspect of the course was chosen to require the skater to perform a movement pattern typically completed during competition: (a) straight ahead sprint, (b) hard cutting change of direction (rt/lt), (c) short acceleration, (d) long acceleration, and (e) crossover (rt/lt). These movement parameters were established from conversations with both NHL and collegiate hockey coaches, as well as from published research (30,31).

Gate 2 fatigue was significantly correlated to $V_{O_{2}}$peak. This time point captured the fatigue rate of each subject during the second half of the course, a time frame of approximately 10–25 seconds of a maximal effort sprint. During this time, the glycolytic pathway is likely the main contributor to ATP production (17,29). One of the main byproducts of the glycolytic pathway is hydrogen ions (H+), causing an associated drop in intracellular pH (10,27), which inhibits the rate-limiting enzymes of glycogenolysis (phosphorylase $a$ and phosphofructokinase [PFK]), and is associated with fatigue (18,29). As a result, fatigue could increase in subsequent bouts of maximal exercise if the muscle is not given sufficient time to clear the H+ from the intracellular space. The rate of recovery for glycolysis is slow, estimated to have a halftime of approximately 9 minutes (19). With the recovery time between sprints during the on-ice test being only 90 seconds, it is unlikely that the glycolytic pathway would be able to return to a homeostatic balance between sprint bouts.
(36). As a result, hockey players with a higher $V_{\text{O}2\text{peak}}$ may be better at buffering $\text{H}^+$. These athletes could raise the pH of their muscle more quickly during recovery, thus giving them an improved rate of recovery during the RSA test; reducing fatigue. Reduced fatigue could also be due to the greater contribution of the aerobic energy pathway during subsequent shifts. As glycolysis is inhibited, aerobic contribution to subsequent performance increases (16). Therefore, it is possible that athletes with higher aerobic capacities were more resistant to fatigue due to enhanced oxidative phosphorylation.

Gate 2 and total course fatigue were also significantly correlated to end stage completed during the skating treadmill test. This association implies that skating mechanics (stride efficiency) on a skating treadmill are an important aspect of on-ice performance. End stage completed can be interpreted as a composite measure of a player’s aerobic capacity and stride efficiency (30). A player with great stride efficiency but a low aerobic capacity has the potential to reach the same end stage as a player with poor stride efficiency and a high aerobic capacity. This is due to the fact that an efficient skater does not require the same amount of energy output to meet a specific workload. Similar phenomena have been seen in endurance athletes and the effect of running economy on marathon times (34). This may also explain why $V_{\text{O}2\text{peak}}$ was not significantly correlated with total course fatigue. $V_{\text{O}2\text{peak}}$ seems to be confounded by hockey players skating economy, as a factor of end stage completed, in that it only accounted for 1.4% of the variance found in total course fatigue. Although this study did not directly measure stride efficiency, our findings of a significant association between end stage completed and on-ice fatigue argue for future research to look more closely at this relationship.

Gate 1 fatigue was not significantly correlated to $V_{\text{O}2\text{peak}}$. With an average time to completion of 9.9 seconds, gate one captured the section of the course most reliant on ATP production from the PCr energy pathway (9). Studies have shown PCr synthesis to follow a biphasic pattern of recovery after intense muscular activity (2). The rate of the fast phase of PCr recovery seems to have a half-time of only 21 seconds, in which 80% of used PCr is resynthesized (21). This seems to be unaffected by the pH of the muscle and is a very robust fatigue-resistant pathway (26). Keeping these facts in mind when examining the parameters of the on-ice repeated shift test gives a possible, justifiable, explanation as to why gate one was not significantly correlated to $V_{\text{O}2\text{peak}}$. The recovery time between sprint bouts was over 4 times longer than PCr requires to recover 80% of its pre-exercise level after maximal exercise. With the primary energy system contributing to gate 1 performance being given sufficient time to recover, the reductions in PCr during repeated bouts are not great enough to elicit measurable fatigue in our sample population of athletes.

Total course time was also not significantly correlated to $V_{\text{O}2\text{peak}}$, however, that could be a factor of the fatigue-resistant nature of the PCr pathway. The significance of total course time, as it relates to $V_{\text{O}2\text{peak}}$, is the sum effect of the energy system taking place during gates 1 and 2. With the recovery of PCr being robust against fatigue, it is plausible that gate 1 times skew the results, reducing the net fatigue effect seen in total sprint time when compared to the athletes $V_{\text{O}2\text{peak}}$. It would stand to reason that a larger sample size, reducing the recovery time, or lengthening the duration of the sprint would have reduced the skew of the data by placing less statistical weight on the fatigue-resistant PCr pathway and increase the effect of oxidative contribution to energy during sprint bouts.

The results of this study indicate that a hockey player’s maximal aerobic capacity is associated with fatigue during a mock hockey shift, and that end stage completed during a graded staking treadmill test is a good predictor of on-ice performance. We hypothesize that this is likely due to the fact that end stage completed takes into account the stride efficiency of the hockey player, in addition to their aerobic capacity. This evidence suggests that it may be prudent for hockey players to emphasize training methods that improve skating efficiency, as well as incorporate $V_{\text{O}2\text{peak}}$-specific training during off-season workouts.

**Practical Applications**

These findings could be beneficial for coaches as they advocate for testing hockey players in a sport-specific manner, through a skating treadmill or on-ice skating test, as the best means of evaluating physical performance during a simulated hockey shift. In addition, these findings could help coaches make decisions about practice time and line configuration. Coaches who have a high number of players who exhibit a high rate of fatigue during the on-ice repeated shift test, or do not reach a high end stage completed during a skating graded exercise test, may want to allocate a larger portion of practice time for skating technique or conditioning to improve sport-specific fitness and reduce injury risk. In addition, coaches may choose to pair players together in line assignments based on their fatigue scores. Players with similar fatigue scores would likely play at, and fatigue at, the same rate. This would allow for more uniform line changes and ensure that 1 player in a line is never substantially more fatigued than his partner.

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Vo\textsubscript{peak} and Repeated Shift Performance

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