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The Association of Countermovement Jump, Isometric Mid-Thigh Pull, and On-Ice Sprint Performance in University Level Female and Male Ice Hockey Athletes

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ABSTRACT

On-ice skating sprint performance is a significant predictor and requirement for playing at the highest levels of hockey. The purpose of this study was to determine the relationship between maximum and dynamic strength measures and on-ice sprint performance in university level ice hockey athletes. Both male (n=18) and female (n=13) hockey players participated in this study. The off-ice measures included two assessment procedures utilizing a force plate; an isometric mid-thigh pull (IMTP) to assess maximum strength and a countermovement jump (CMJ) to assess dynamic strength. Both off-ice measures were analyzed from both a relative (CMJr and IMTPr) and absolute (CMJa and IMTPa) perspective. The on-ice measures were 7.71m and 15.42m sprint times. Pearson product moment correlations were used to quantify the relationships between variables. CMJa (r = -0.56 to -0.61), IMTPa (r = -0.65 to -0.67) and IMTPr (r = -0.55) were significantly correlated (p < 0.05) with on-ice sprint performance. When analyzed by sex, no significant relationships (p > 0.05) were observed between CMJ measures and on-ice sprint times. No significant relationships (p > 0.05) were observed between IMTP measures and on-ice sprint times when individually analyzing male participants, while significant relationships (p < 0.05) were observed in females between IMTPa (r = -0.70 to -0.71) and IMTPr (r = -0.68 to -0.71) and on-ice sprint times. It is concluded that both maximum and dynamic strength are important factors in on-ice sprint performance in hockey players. Furthermore, maximum strength seems to be an important characteristic in on-ice sprint ability in females.

Keywords: ice hockey, sprint performance, skeletal muscle strength

INTRODUCTION

Ice hockey is a high-speed, collision sport that requires the athlete to possess many athletic performance characteristics. One of the most important performance parameters needed to play at the highest levels in ice-hockey is on-ice sprinting as players frequently need to reach high speeds in short amounts of time (Farlinger et al. 2007; Peterson et al. 2015).

While some studies have evaluated the relationship between on-ice skating performance and off-ice performance tests, there is a paucity of literature surrounding how on-ice sprint skating correlates with off-ice performance variables that can be assessed on a force plate (Behm et al. 2005; Peterson et al. 2015; Janot et al. 2015). There is a strong relationship between maximum strength and running/sprinting performance in a variety of field sport athletes; however, little research has been completed to assess the relationship between maximum strength, as assessed by 1-repetition maximum testing, and on-ice sprint skating performance (Behm et al. 2005; Peterson et al. 2015; Janot et al. 2015). Further, there are many instances in the reported literature where tests of dynamic strength (e.g., vertical jump, broad jump) have correlated highly with on-ice sprint performance. Recently, there has been the introduction of a new, more efficient method of assessing dynamic and maximum strength among strength and conditioning professionals: countermovement jump (CMJ) and isometric mid-thigh pull (IMTP) using force plate technology (Sheppard et al. 2011; Thomas et al. 2015).

The use of force plate testing procedures such as the IMTP and CMJ have been shown to be valid and reliable measures of lower body strength and power, respectively (Haff et al. 1997; Sheppard et al. 2011; Thomas et al. 2015). A force plate allows the measurement of maximum and dynamic strength levels in a large group setting, typical across all sports and levels of strength and conditioning programs. In the past, strength testing would be performed utilizing a variety of methods (such as 1-RM), all of which present varying levels of safety, planning, and time commitment issues. 1-RM testing requires the use of multiple spotters depending on the type of exercise being performed whereas force plate testing utilizing the IMTP and CMJ protocols presents relatively little safety concerns and one operator.

The relationship between on-ice sprint performance, IMTP and CMJ has not been investigated. Very limited research of this nature has been conducted with female hockey players. Due to increasing prevalence, utility and validity of force plate testing procedures, this relationship warrants further investigation in the male and female hockey populations. This information will help to uncover the value of two types of strength (maximum strength or dynamic strength) in males and females for one aspect of the sport of hockey, specifically on-ice sprint performance. The purpose of this study was to evaluate the relationship between two off-ice performance testing variables utilizing a force plate (maximum strength via IMTP and dynamic strength via CMJ) and on-ice sprint performance. The hypothesis of this research was that there would be significant negative correlations between absolute and relative dynamic strength with on-ice sprint times while there would be no significant relationship between absolute and relative maximal strength and on-ice sprint performance.

METHODS

Experimental Design

The study was designed to investigate the relationship between off-ice force plate performance measures (IMTP and CMJ) and on-ice skating sprint speed in collegiate ice hockey players. To establish correlations between off-ice and on-ice variables, measurements consisted of the IMTP and CMJ which were performed, calculated, and compared to on-ice sprint ability over 7.71m and 15.42m (time).

Participants

A sample size calculation was performed, and it was anticipated that to reach statistical significance at $\alpha < 0.05$ and $\beta = 0.20$, with a previous correlation coefficient of $r = -0.55$ (between vertical jump height and the on-ice skating velocity over 90 feet), that a sample size of 24 participants would be required for the current study (Runner et al. 2016). University level hockey athletes ($n = 31$) were recruited for participation in this study. Inclusion criteria included current participation as a student-athlete on the men's or women's hockey team and a minimum of 1-year of experience in a structured strength and conditioning program (Boland et al. 2019). Exclusion criteria required that the participants were free of any musculoskeletal injury that may inhibit maximal effort performance of all testing procedures, as determined by the team's Certified Athletic Therapist. Randomization of testing order was implemented to protect against potential order effect and was implemented by randomizing the testing order of off-ice and on-ice testing and order of CMJ and IMTP testing. Participants were instructed to abstain from alcohol, vigorous physical activity, and heavy weightlifting 48 hours prior to testing. Participants were verbally informed of the procedures and were asked to provide written informed consent prior to participation. The study received ethical approval from the institutional Research Ethics Board (HS21634).

Procedures

Off-Ice Procedures

Height was measured prior to warm-up using a standard stadiometer (Charder - HM230M, Bellevue, Washington State, USA) and weight was measured by the force plate software as part of the force plate testing procedures. Prior to testing the CMJ and IMTP, the athletes underwent a standardized warm-up consisting of a supervised, 5-minute dynamic warm-up followed by 2-repetitions of the CMJ (at maximal intensity) and 2-repetitions of the IMTP (where 1-repetition was held for 3-seconds at 50% of the athletes self-selected maximal intensity and 1-repetition was held for 3-seconds at 75% of the athletes self-selected maximal intensity). Both repetitions of the CMJ and IMTP allowed for familiarization and were separated by 1-minute of passive rest. Two trials of each test (CMJ and IMTP) were performed in a randomized order and each trial was separated by 1-minute of passive rest. Upon completion of the first off-ice test, 5-minutes of passive recovery was given to allow for complete recovery of the phosphagen energy system. The participant then proceeded to complete the second off-ice test. The highest peak force produced for both the CMJ and IMTP was used for analysis. It is important to note that in addition to the familiarization trials, all participants were familiar and had completed these testing procedures previously as part of their regular team intake testing protocol.

Figure 1A. Force plate CMJ demonstration.

Figure 1B. Force plate IMTP demonstration.

The CMJ test required the athlete stand with their hands holding a dowel on their back and their feet on the force plate (Quattro Jump, Kistler USA, Amherst, NY, USA) (see Figure 1A). A dowel was utilized to control for use of the upper body during the CMJ. The athlete self-selected their squat depth to produce a jump with the most power and height possible. The athlete was given a "ready" command, and then given a "go" command by the operator when the jump was to be initiated. Each athlete was instructed to jump as high as they could, as quickly as they could, all while keeping the dowel in contact with their shoulders and sticking their landing on the force plate. Rest time between trials was 1-minute.
The mid-thigh position was marked between the anterior superior iliac crest and patella by the primary investigator and the athletes self-selected their knee and hip angles (Wang et al. 2016). They were instructed visually and verbally to stand in the universal athletic position which requires "triple flexion" of the ankles, knees and hips, plus neutral spine position (see Figure 1B). They were then instructed to have the bar rest at the position at which they felt strongest (Wang et al. 2016). The IMTP bar used had the same width and diameter as a standard barbell. Participants were only allowed to utilize an overhand grip. Each participant was provided wrist straps to maintain their grip when executing the IMTP test and were provided assistance in order to apply the straps appropriately. Once the athlete found their starting position on the force plate, they were given a "ready" command, and then given a "go" command by the operator at which point the participant exerted maximal downward vertical force for 5-seconds while maintaining a neutral spine position. Verbal encouragement was provided by the operator to ensure maximal effort was achieved. Each athlete was instructed to maintain their overhand grip, push through their feet into the force plate, maintain neutral spine posture and apply maximal force for the entire 5-seconds. A single repetition of the IMTP was performed and provided a proper warm-up is completed, this method has been shown to produce a valid assessment of maximum strength (De Witt et al. 2018).

For both the CMJ and IMTP, relative and absolute measures of dynamic and maximum strength, respectively, were analyzed. Absolute measures included peak kilograms of force (kgf) for both the IMTP and CMJ. Relative measures included peak kilograms of force/kilogram of body mass (kgf/kg) for the IMTP and CMJ. This data was captured by the force plate (Quattro Jump, Kistler USA, Amherst, NY, USA) sampling at 500Hz.

On-Ice Procedures

On-ice testing procedures took place at the university hockey arena. The athletes underwent a standardized warm-up consisting of a supervised, 5-minute off-ice dynamic warm-up plus a 3-minute warm-up of light skating and shooting. The on-ice testing was performed in full hockey equipment with skates sharpened to personal preference. Sprint ability was assessed by having the participant sprint, from a stationary start, blue line to blue line (distance = 15.24m). Similar protocols have been implemented in earlier research, and the method is considered a valid measure of sprint ability (Bracko and George 2001; Peterson et al. 2015). The participant started by standing with their front skate directly behind the blue line (starting line), stick in hand. When the participant felt they were ready, they sprinted as fast as possible through the second blue line (finish line). Time was recorded by Smart Speed wireless timing gates (Fusion Sport, Chicago, IL, USA). Timing gates were placed at the beginning (0m), middle (7.71m), and end (15.42m) of the sprint distance. The timing gate lasers were placed at chest level of the participants to ensure that the laser timed the body crossing the line, not the stick. In addition, participants were told to keep their sticks on the ice to ensure they did not prematurely trip the laser timer. Once the participant crossed the finish line, they coasted back to the start line and were given 5-minutes to recover. Participants performed 2 sprint trials and the best time was used for analysis as is common in similar past studies comparing sprint performance to other performance assessments (Farlinger et al. 2007; Peterson et al. 2015; Runner et al. 2016; Rey et al. 2017). The recovery time started when the participant returned to the starting line. Similar tests have been reported to have test-retest values of r=0.8 (Bracko and George 2001).

Statistical Analyses

The Shapiro-Wilk test was conducted to test normality of each variable and it was found that all variables met the criteria for normalcy. Means and standard deviations (SD) were calculated for all variables. Pearson product-moment correlation analysis was used for all variables. Variables used for analysis included each participant's peak force output in both the IMTP and CMJ and their best on-ice sprint times. Data were analyzed using SPSS v22.0 software (SPSS, Inc., Chicago, IL, USA). Correlations were evaluated using the following criteria: small = 0.1–0.29, moderate = 0.30–0.49, large = 0.50–0.69, very large = 0.70–0.89, nearly perfect = 0.90–0.99, and perfect = 1.0 (Hopkins et al. 2009). An alpha level of $p < 0.05$ was considered statistically significant for all comparisons.

RESULTS

Descriptive statistics of participants are depicted in Table 1. Briefly, a total of 31 university hockey players (n=13 females, n=18 males) participated in the study. Descriptive statistics for 7.71m sprint time, 15.42m sprint time, CMJ, and IMTP results are depicted in Table 2.

The Relationship Between On-Ice Sprint Performance and CMJ

When females and males were analyzed as a whole group, 15.42m and 7.71m on-ice sprint times significantly correlated with CMJa peak force (r = -0.61, $p < 0.05$; r = -0.56, $p < 0.05$) respectively (see Table 3). CMJr peak force produced a non-significant correlation with 7.71m and 15.42m on-ice sprint time (r = -0.26, $p > 0.05$; r = -0.31, $p > 0.05$) respectively (see Table 3).

The results of the correlational analysis when only considering male participants produced no significant relationships (all $p > 0.05$) between dynamic strength (as determined by the CMJ) and on-ice sprint times (see Table 4).

The results of the correlational analysis when only considering female participants produced no significant relationships (all $p > 0.05$) between on-ice sprint times and CMJ variables as seen in Table 5.

The Relationship Between On-Ice Sprint Performance and IMTP

When all participants were analyzed as one group, all measures of the IMTP were significantly correlated with both 15.42m and 7.71m on-ice sprint times. IMTPa peak force (r = -0.67, $p < 0.05$) and IMTPr peak force (r = -0.55, $p < 0.05$) were significantly correlated with 15.42m on-ice sprint time. IMTPa peak force (r = -0.65, $p < 0.05$) and IMTPr peak force (r = -0.55, $p < 0.05$) were significantly correlated with 7.71m on-ice sprint time.

The results of the correlational analysis when only considering male participants produced no significant relationships (all $p > 0.05$) between maximum strength (as determined by the IMTP) and on-ice sprint times.

The results of the correlational analysis when only considering female participants produced significant relationships between maximum strength and on-ice sprint times. IMTPa (r = -0.71, $p < 0.05$) and IMTPr (r = -0.68, $p < 0.05$) were significantly correlated with 15.42m on-ice sprint time. IMTPa (r = -0.70, $p < 0.05$) and IMTPr (r = -0.71, $p < 0.05$) were significantly correlated with 7.71m on-ice sprint time.

Table 1. Participant Descriptive Characteristics for Females (n=13) and Males (n=18). Data are means ± SD.

Characteristic	Combined (N=31)	Males (n=18)	Females (n=13)
Age (years)	22.3 ± 2.1	23.7 ± 1.1	20.4 ± 1.3
Height (cm)	152.8 ± 8.6	158.4 ± 5.3	145.1 ± 5.7
Weight (kg)	79.9 ± 12.7	88.8 ± 8.4	67.6 ± 4.6

Table 2. On-Ice and Off-Ice Tests Descriptive Characteristics.

Variables		Females		Males		Combined	
		Mean	SD	Mean	SD	Mean	SD
Off-ice	CMJa (kgf)	153.07	16.80	211.94	25.61	187.26	36.83
	CMJr (kgf/kg)	2.26	0.16	2.39	0.22	2.34	0.21
	IMTPa (kgf)	225.23	35.84	333.06	45.61	287.84	67.96
	IMTPr (kgf/kg)	3.31	0.32	3.77	0.50	3.58	0.48
On-ice	7.71m (sec)	1.64	0.09	1.55	0.05	1.59	0.08
	15.42m (sec)	2.80	0.12	2.66	0.89	2.72	0.12

Mean off-ice and on-ice variable responses for females (n=13), males (n=18), and combined data (N=31).
Note: CMJa = Countermovement jump absolute, CMJr = countermovement jump relative, IMTPa = Isometric mid-thigh pull absolute, IMTPr = Isometric mid-thigh pull relative.

Table 3. Correlational Analysis of On-Ice and Off-Ice Tests for Males (n=18) and Females (n=13) Combined (n=31).

Off-Ice Variables	On-Ice Variables	
	7.71m	15.42m
CMJa	-0.56*	-0.61*
CMJr	-0.26	-0.31
IMTPa	-0.65*	-0.67*
IMTPr	-0.55*	-0.55*

$p < 0.05$

Note: CMJa = Countermovement jump absolute, CMJr = countermovement jump relative, IMTPa = Isometric mid-thigh pull absolute, IMTPr = Isometric mid-thigh pull relative.

Table 4. Correlational Analysis of Males (n=18) On-Ice and Off-Ice Variables.

Off-Ice Variables	On-Ice Variables	
	7.71m	15.42m
CMJa	-0.34	-0.37
CMJr	-0.38	-0.30
IMTPa	-0.20	-0.27
IMTPr	-0.26	-0.28

$p < 0.05$

Note: CMJa = Countermovement jump absolute, CMJr = countermovement jump relative, IMTPa = Isometric mid-thigh pull absolute, IMTPr = Isometric mid-thigh pull relative.

Table 5. Correlational Analysis of Females (n=13) On-Ice and Off-Ice Variables .

Off-Ice Variables	On-Ice Variables	
	7.71m	15.42m
CMJa	-0.32	-0.35
CMJr	-0.13	-0.11
IMTPa	-0.70*	-0.71*
IMTPr	-0.71*	-0.68*

$p < 0.05$

Note: CMJa = Countermovement jump absolute, CMJr = countermovement jump relative, IMTPa = Isometric mid-thigh pull absolute, IMTPr = Isometric mid-thigh pull relative.

DISCUSSION

The primary purpose of this study was to investigate the associations between IMTP and CMJ peak force production and on-ice sprint performance in collegiate ice-hockey players. It was hypothesized that measures of maximum strength (IMTPa and IMTPr) as well as dynamic strength (CMJa and CMJr) would be significantly correlated with on-ice sprint performance. The results of the analysis of all participants combined indicated that IMTPa, IMTPr and CMJa were significantly correlated with 15.42m and 7.71m on-ice sprint times. However, no significant correlations were found between CMJr and on-ice sprint times. To our knowledge, this is the first study to compare force plate strength testing protocols and on-ice sprint performance in ice-hockey athletes.

Absolute lower body dynamic strength (CMJa) was related to on-ice sprint performance when all participants were analyzed which agrees with the hypothesis of the study. The present study produced large and significant correlations between CMJa and both 15.42m and 7.71m on-ice sprint times. This is consistent with previous results in which vertical jump (VJ) was shown to significantly correlated with on-ice sprint performance of similar distances (Farlinger et al. 2007; Runner et al. 2016).

Some research indicates that on-ice sprint performance is an important characteristic of elite level hockey players (Bracko and George 2001). Despite this, there has been little investigation into the strength qualities associated with on-ice sprint performance. More effort has been expended in identifying the strength qualities associated with sprinting in competitive sprinters and field sport athletes (Cronin and Hansen 2005; Cronin et al. 2007; McBride et al. 2009; Loturco et al. 2015). Though sprinting on-ice with skates and sprinting on ground with shoes are different tasks, previous research has shown that off-ice sprint performance is related to on-ice sprint performance (Bracko and George 2001; Farlinger et al. 2007; Krause et al. 2012). Furthermore, the same two factors that contribute to both on-ice and off-ice sprint performance are stride rate and stride length, so comparisons can be drawn between both tasks (Farlinger et al. 2007). Generally, ice sprint skating has a longer ground contact time and slower stride frequency compared to sprinting in other sports using different surfaces, such as a track (Robert-Lachaine et al. 2012; Nagahara et al. 2014). A strong relationship between off-ice and on-ice sprint performance is observed because they are tasks that require both leg power which directly affects stride length, and leg speed which directly affects stride rate (Mascaro et al. 1992). Krause et al., (2012) found the off-ice 40-yard sprint time to be the best predictor of the on-ice 34.5m sprint time in elite high school male hockey players. Though the task requires different biomechanical qualities, the relationship between dynamic strength and both on-ice and off-ice sprint performance seems to be similar. The similarities between off-ice and on-ice sprint performance will aid in the understanding of the strength qualities associated with on-ice sprint performance.

Off-ice and on-ice sprint performance consistently showcase strong relationships with tests of dynamic strength such as the VJ measured in height or the CMJ measured in peak force output (Cronin and Hansen 2005; Requena et al. 2011; Marques and Izquierdo 2014; Loturco et al. 2015; Runner et al. 2016). The present study found a significant relationship between CMJa peak force output and on-ice sprint performance, meaning that the participants who produced higher absolute peak force during the CMJ also tended to skate faster over both 7.71m and 15.42m. The relationship between CMJ performance and sprinting performance is highly correlated and has been demonstrated in multiple studies (Cronin and Hansen 2005; Requena et al. 2011; Marques and Izquierdo 2014; Loturco et al. 2015). However, there is only one study, to our knowledge, that has assessed the relationship between ice hockey sprinting performance and CMJ performance (Runner et al. 2016). As off-ice and on-ice sprinting share many characteristics, we can surmise that improvements in absolute peak force production in the CMJ could result in improved on-ice sprint performance. Based on the results from the previous study (Runner et al. 2016) in which the VJ height was found to be the best off-ice predictor of on-ice speed and the current study, we can conclude that absolute lower body dynamic strength is related to on-ice sprint ability.

Relative lower body dynamic strength (CMJr) was not significantly correlated with on-ice sprint performance. This was not in agreeance with the current study's hypothesis. Previous results have not included relative measures of dynamic performance measures in tests such as the VJ, CMJ or broad jump. The lack of association between CMJr and on-ice sprint performance is surprising since 1 of the 2 factors that affect skating performance is stride length which is enhanced by improving relative leg power (Mascaro et al. 1992). Furthermore, previous research has shown CMJ performance to be significantly correlated with off-ice sprint performance (Cronin and Hansen 2005; Requena et al. 2011). Moreover, Baker and Nance (1999) found that relative dynamic and maximum strength measures showed stronger relationships to sprint performance in rugby players compared to absolute measures. A possible explanation could be less friction experienced since skating occurs on an ice surface. Because the coefficient of friction experienced when skating is much lower than ground-based sprinting, there is much less opposing force to the athlete's stride(s). The lack of opposing force may play a factor in horizontal velocity. Skating athletes that apply the highest amounts of absolute force production may actually be at an advantage as greater absolute peak force production results in greater rates of horizontal velocity (Thomas et al. 2015; Wang et al. 2016). Athletes with the highest CMJa peak force outputs do not produce the highest CMJr peak force outputs due to the effect of body weight which is another potential reason for the lack of correlation observed between CMJr and on-ice sprint performance. Thus, the athlete who jumps higher by applying more absolute peak force into the ground seems to skate faster. Another possible explanation would be the lower variability in bodyweight within the participants of the current study in comparison to the variability within the participants' CMJa peak force production of the lower body. With regards to the present study, more variability was observed in CMJa peak force values compared to bodyweight values. Perhaps if bodyweight values showcased the same or similar amount of variability as CMJa peak force, we may have observed a higher value of r for CMJr and on-ice sprint performance.

There seems to be a relationship between absolute dynamic strength and on-ice sprint performance. Previous research has demonstrated that there is a meaningful relationship between vertical jump performance and both on-ice and off-ice sprint performance. It was found that measures of dynamic strength have a non-significant association with on-ice sprint performance when males and females were analyzed separately. This contrasts the results of Farlinger et al. (2007) and Runner et al. (2016) where both studies found significant correlations between VJ and on-ice sprint performance; however, it should be noted that the on-ice sprint distances considered in each situation were different between the studies and range from 7.71m to 35m. Furthermore, peak force (kgf) in the CMJ was compared with on-ice sprint time in the current study compared to VJ height (cm) in previous studies. Though measuring peak force compared to jump height is different, they have been shown to be related as athletes who produced higher jump heights in the CMJ, also produced the highest peak force outputs at key points during the CMJ (Kraska et al. 2009). Peterson et al. (2006) also found that VJ height and VJ peak power produced correlations that were strong and significant in a large group of male and female collegiate athletes which is important as high peak power production requires high amounts of peak force production. Previous research shows that peak force production and vertical jump height are related, though this difference in variables examined (peak force vs. jump height) could have potentially caused the large shift seen in the strength of association between dynamic strength and on-ice sprint time. Despite this difference in variables examined, we expected to see similarities in the strength of association between the studies since all tests are tests of the same physical ability: dynamic strength.

It was surprising to find a lack of significant correlations between CMJa and CMJr with on-ice sprint performance in males specifically since previous investigations showcased a strong relationship between jump ability and on-ice sprint performance (Farlinger et al. 2007; Runner et al. 2016). In one study they found that the direction of impulse application is more important to improve sprint acceleration than simply producing larger magnitudes of (resultant) impulse irrespective of its direction during ground contact (Kawamori et al. 2013). This is a possible explanation as to why CMJ peak force values produced no significant correlations with on-ice sprint performance in male hockey players. The direction of force application measured in the CMJ is vertical, whereas the direction of force application during on-ice sprint performance is a combination of vertical, horizontal, and lateral. This difference in direction of force application may be a reason we did not observe a relationship between CMJ peak force values and on-ice sprint time.

Absolute and relative lower body maximum strength (IMTPa and IMTPr) were shown to be significantly correlated with on-ice sprint performance. This result is not in agreeance with the present studies' hypotheses. Based on previous research that assessed the relationship between maximum strength and on-ice sprint performance, we did not hypothesize that IMTP peak force values would significantly correlate with on-ice sprint performance (Behm et al. 2005; Janot et al. 2015; Runner et al. 2016). Despite our hypothesis, a relationship seems to exist between maximum strength and on-ice sprint performance, and previous research has shown that maximum strength is associated with off-ice sprint ability. In the current study, strong and significant correlations were observed between IMTPa and 15.42m and 7.71m on-ice sprint times. From this data, though it is correlational, we can infer that there is a potentially meaningful relationship between lower body maximal strength and on-ice sprint performance.

Sprint performance seems to be associated with relative lower body maximum strength. Edman & Esping (2013) analyzed the relationship between 1-RM squat and 17.5m on-ice sprint in Elite Junior Swedish hockey players (average age = 17.8+/-0.8). A statistically significant relationship was observed between absolute 1-RM squat ($r = -0.60$, $p < 0.05$) and relative 1-RM squat ($r = -0.61$, $p < 0.05$) with 17.5m on-ice sprint ability. Athletes that engage in lower body strength training experience improvements in lower body maximal strength, jump ability and sprint ability. Therefore, there is previous literature which corroborates the findings of the present study and provides preliminary evidence that lower body maximum strength is related to on-ice sprint performance in hockey players.

It was found that measures of maximum lower body strength have a much larger strength of association with on-ice sprint performance in females compared to males. For females, both IMTPa and IMTPr were significantly correlated with on-ice sprint performance. For males, none of the measures of maximum strength were significantly correlated with on-ice sprint performance. This result was somewhat surprising as the hypothesis was based on previous research (Janot et al. 2015; Runner et al. 2016), which included both male and female participants, but was predominantly male. Both studies found a small strength of association between 1RM back squat and on-ice sprint performance but only one study included females in their analysis. The present study's hypothesis was that maximum strength would not be significantly correlated with on-ice sprint performance. However, the studies that informed our hypothesis, and specifically the two referenced above, analyzed the relationship between maximum strength and on-ice sprint performance in predominantly males only. On the contrary, very little research of this nature has been conducted with females which makes this an interesting and novel finding.

Healy et al. (2019) performed the same maximum strength assessment as the present study and assessed the relationship between absolute and relative peak force measures with 10m and 40m sprint performance in international and national level female sprinters. They found no significant correlations between IMTP measures and 10m and 40m sprint performance. It is very interesting that IMTP measures are strongly and significantly correlated with on-ice sprint performance in female hockey players yet show a very weak strength of association in female sprinters. Perhaps the differences in training history and training age between the two groups of participants being analyzed contributed to the differing relationships. Peterson et al. (2006) conducted a study with Division 1 collegiate athletes in the United States, 35 of which were females, and assessed the relationship between maximum strength and sprint performance. The females in this study would be much more closely related to the females in the present study in the areas of training age and training history as both groups are of similar age and level of competition. Peterson et al. (2006) found that 1-RM squat was significantly correlated with sprint acceleration and sprint velocity which aligns with our findings. The previous study compared maximum strength to sprint acceleration rates over 20m and to sprint velocity rates over 40m, whereas the present study compared maximum strength with on-ice sprint times over 7.71m and 15.42m. This is important to note, as it is obvious that these tests are different in both distances covered and variables measured (time vs. m/sec), but still produce comparable data points as it has been shown previously that off-ice sprint performance is significantly correlated to on-ice sprint performance in female hockey players (Bracko and George 2001; Janot et al. 2015). According to the present study results, maximum strength is related to on-ice sprint performance in females. The present study found that IMTPa and IMTPr were significantly correlated with on-ice sprint performance in females.

When specifically analyzing males, our results support our hypothesis that maximum strength would not be significantly correlated to on-ice sprint performance. This hypothesis was based on previous research that found no significant correlations between tests of maximum strength and on-ice sprint performance of varying distances (Janot et al. 2015; Runner et al. 2016). Perhaps one reason for the large difference in the strength of association between maximum strength and on-ice sprint performance in males versus females is the differences observed in skating kinematics. Shell et al. (2017) compared movement kinematics of the skating start between elite male and female hockey players. It was found that males exhibited significantly greater knee flexion angles and hip abduction range of motion (Shell et al. 2017). The greater knee flexion angles observed in males may be a contributing factor to the lack of correlation observed between IMTP measures and on-ice sprint performance in males due to the limited knee flexion angles exhibited during IMTP testing protocols.

It is possible that females showcased a much stronger relationship between maximum strength and on-ice sprint performance due to specificity of the IMTP testing protocol as females exhibited significantly less knee flexion compared to males when accelerating during skating (Shell et al. 2017). This may be a key factor contributing to the large differences observed in the relationship between maximum strength and on-ice sprint performance in males and females. Because of the unique and novel blend of kinematic variables observed during the task of skating, and the increased range of motion observed in males compared to females, factors such as skating technique and efficiency may play a larger role than maximum and dynamic strength qualities. Further study would be needed to confirm or deny such a statement, but when combining the findings of the present study and those of the aforementioned study, there is reasonable evidence. Typically, most high performance sprint skaters adopt more hip and knee flexion during the skating movement pattern which translates to higher velocities for these athletes (Upjohn et al. 2008; Buckeridge et al. 2015; Neeld 2018).

The findings of this study must be seen in light of some limitations. This study was correlational in nature and therefore we cannot establish cause and effect, and the directionality of that relationship, with certainty. Another limitation of the study was that we did not determine fat-free mass. This could have been done to aid in the assessment of amount of force produced per kilogram of fat-free mass and may have aided in the understanding of the relationship between off-ice maximum and dynamic strength with on-ice sprint performance. Another potential limitation was in the variables that we examined from our off-ice force plate testing data. Because we were especially interested in the relationship between peak force production and on-ice sprint ability, we failed to assess other potentially significant variables related to off-ice force production (for example, rate of force production).

This study confirms previous relationships relating off-ice jump performance to on-ice sprint performance and adds new insight to our understanding of the relationship between maximum strength and on-ice sprint performance. It is important to note, that a caveat must be placed on any conclusions regarding the relationship between off-ice maximum and dynamic strength abilities and on-ice sprint performance because of the complex nature of hockey skating, which itself, can limit players from performing at high levels. Just because a player can produce excellent scores in the off-ice test(s) that have the strongest correlation with on-ice sprint ability, certainly does not guarantee that they will be an elite level skater due to the complexity and skill required. The goal of the present analysis was to highlight the importance of dynamic and maximum strength as they relate to on-ice sprint performance. Future research is needed to investigate how changes in physical ability tests such as the IMTP and CMJ impact on-ice sprint performance.

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