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Functional Performance Testing in Ice Hockey: the Role of the Single Leg, Medial Countermovement Jump

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Abstract

Due to the physical nature of the game, injuries are common in ice hockey. Injury rates have been difficult to interpret due to the inconsistencies in the definitions of injury and athlete exposure. Consensus statements on injury definitions have been developed for sports such as soccer and rugby but have not been established in ice hockey. Furthermore, many different off-ice tests are performed, but a hockey-specific performance test has not been promoted. Accordingly, the objective for this thesis was to investigate injury rates, injury definition, athlete exposure and injury type in men's ice hockey, and providing information on a practical test practitioners can use to monitor fatigue and measure performance. This was achieved through three research projects. An integrative literature review was conducted to suggest a specific definition of injury and athlete exposure (Chapter 2). This study identified that the International Ice Hockey Federation's definition of injury is preferred based on the clarity and relevance of the injury description and that the preferred athlete exposure metric is player game-hours based on accuracy and ease of use. In addition, lower extremity injuries were identified as common and costly in men's ice hockey. The single leg, medial countermovement jump was identified as an appropriate hockey-specific performance test. This jump enables objective measures of frontal plane force and power and is particularly applicable for ice hockey players given that ice skating involves applying lateral forces. All twelve parameters of the jump showed moderate to excellent reliability (Chapters 3) suggesting that this jump is a reliable test for assessing frontal plane force and power in ice hockey players. Finally, normative values and asymmetry indices were presented in ninety-one male youth hockey players aged 10–18 years (Chapter 4). In conclusion, lower extremity injuries are common in hockey and injury rates are difficult to interpret as the definition is not consistent. The single leg, medial countermovement jump is an appropriate functional test for measuring skating performance. Ice hockey performance staff can use this evidence-based research to measure performance, monitor fatigue, and document recovery from injury.

Keywords

youth ice hockey, neuromuscular power, reliability, functional performance test, jumping, athlete monitoring

Summary for Lay Audience

Ice hockey is one of the most popular sports played in North America. Due to the physical nature of the game, injuries often occur. Injuries in men's elite ice hockey have been studied over the past 40 years, however, there is a lack of consensus on definitions of both injury and athlete exposure. These inconsistencies make it difficult to evaluate injury rates over time or between hockey leagues.

Players' skill and physical development change with age resulting in increased upper body strength and lower body power. Consequently, physical preparation training and functional performance testing are important for measuring performance and monitoring fatigue. These tests may also be used to evaluate whether injured players are recovered and able to return to play. Numerous tests have been used in hockey, as illustrated by the NHL Scouting Combine™; however, the best tests must be selected based on reliability and relevance to sport. This thesis proposed that the single leg, medial countermovement jump is an appropriate performance test for ice hockey as it involves pushing to the side, like skating.

This study determined that all twelve parameters of the single leg, medial countermovement jump were reliable enabling coaches to feel confident when testing their athletes. Normative values and asymmetry indices were also presented for ninety-one youth hockey players. These values provide age-specific reference to coaches and performance staff. This permits coaches to compare their athletes' performance with other athletes playing the same level of hockey. The results of this thesis provide evidence that parameters of the single leg, medial countermovement jump can reliably be used in the sport of ice hockey. Performance specialists can use this information to assess performance, monitor fatigue, and document recovery from injury.

Co-Authorship Statement (where applicable)

This thesis contains material from two manuscripts that have been published (Chapter 2 and Chapter 3) and one submitted manuscript (Chapter 4) that encompass the collaborative work of researchers and co-authors. Anthony Donskov is the primary author of all of the chapters contained in this thesis. Dr. James P. Dickey (Professor in the School of Kinesiology, Faculty of Health Science, Western University) co-authored Chapters 2-4. David Humphreys (School of Kinesiology, Faculty of Health Sciences) co-authored Chapter 2. Dr. Jeffrey Brooks (Postdoctoral Fellow in the School of Kinesiology, Faculty of Health Sciences), co-authored Chapter 3-4.

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Chapter 1

1 Introduction: Background and Rationale

Ice hockey is a fast, exciting sport. Unfortunately, injuries occur due to the physical nature of the game. It is important to track injury rates in order to compare inter league injury data and assess injury trends across time. Injury rates vary from as low as 13.8/1000 player games [1] to as high as 121/1000 player-game hours [2] depending on the level of play and the way that injury rates are defined. Unfortunately, studies use differing definitions of both components of injury rates (injury and athlete exposure).

Different definitions have been described based on whether medical attention is required, or whether the injury caused the player to miss practices or games [3]. The various injury definitions include "all complaints", where any complaint by the athlete is defined as an injury, "medical attention" which defines an injury only if it deems attention from a medical professional, and finally "time loss" which defines an injury that causes a player to miss one or more games or practices. Youth [4], junior [2,5], collegiate [6], international [7-9], and professional leagues [10] all define injuries differently. Inconsistent definitions make it difficult to evaluate cross-sectional data across various leagues.

In addition, the definition of athlete exposure differs between studies [5,9,11,12]. An athlete exposure is defined as one athlete participating in a practice or game in which there is a potential for athletic injury [13] and is typically expressed as injuries per 1000 games, or injuries per 1000 game-hours.

These types of inconsistencies prompted soccer to create an injury consensus group, which developed consensus statements on injury definitions and data collection procedures in soccer [14]. This group was composed of experts involved in the study of soccer injuries. Injury definition and criteria for classifying injuries with regards to location, type diagnosis and causation were proposed [14]. In addition sports such as rugby union [15], track and field [16] and the International Olympic Committee [17] have also formed consensus statements to define health-related incidents (injuries and illnesses). These statements identify information that should be recorded in epidemiological studies in athletics, and the criteria for recording their nature, cause and severity, as well as standards for data collection and analysis procedures [17]. These procedures enable for consistency and efficiency amongst performance professionals during data collection.

Lower extremity injuries are extremely prevalent in ice hockey [18-20]. At the youth levels, lower extremity injures account for 16-40% of all injuries [21-24]. Based on data collected from the National Electronic Injury Surveillance System (NEISS) from 2001-2002, an estimated 32,750 adolescents with ice hockey related injuries were treated in US emergency facilities, including more than 18,000 under the age of 18 years old [22]. There was a total of 3,029 lower extremity injuries, representing 16.1% of all ice hockey related injuries treated in US emergency facilities. The junior, collegiate and professional levels of ice hockey have also identified the lower extremity, specifically the knee joint, as the most common location for lower extremity injury [1,11,12,18,19,25,26]. At the collegiate level, knee injuries represent 13.5% of all injuries in games and 10.1% of all injuries in practices [27]. Knee injuries such as MCL strains may take up to 8 weeks to heal depending on the grade of the injury [28] while surgical intervention of hip femoacetabular impingement may take 3-4 months post-surgery to participate in skating [29]. Having a reliable and valid lower-extremity test can be used to track performance, and guide recovery during a lower extremity injury.

Returning to sport after a lower-extremity injury requires open communication and planning from player, coach, and rehab specialist. During this time, a structured program is created that respects tissue healing timelines [30] and the athlete's sporting background [31]. Progress is measured in several ways including passive and active range of motion, and stabilization, strength and power assessments. The need to individualize rehabilitation is critical. One approach is the functional testing algorithm (FTA). The FTA is an objective, quantitative and qualitative method to assess a patients progress from immediate post-surgery to complete return to sport [32]. The FTA involves various measures of progress including basic measurements, isokinetic testing, functional jump testing, functional hop testing and sports-specific testing. Many of the published strength and power assessments involve single leg hopping for distance in varying directions [33-35]. Distance-based tests do not directly measure parameters such as ground reaction force, impulse and power which can be used to better objectify neuromuscular fatigue [36,37], and return to play timelines [38]. In addition, these distance-based tests do not measure jump strategy variables such as center of mass depth, unload, yielding and braking time. Researchers have identified significant associations between bi-lateral countermovement jump performance metrics and jump strategy metrics involving the center of mass [39]. Jump strategy has also been investigated for the single leg countermovement jump in English Championship football (soccer) [40] . Movement strategy was quantified as force-time history metrics differentiating between eccentric and concentric phases of the jump. Researchers concluded that greater rate of force development in both phases produced the highest jumpers [40]. Finally, countermovement jump movement strategy differences have been identified in professional soccer players with previous injury despite not showing any performance deficits [38]. Previously injured athletes showed significantly greater asymmetry in concentric and eccentric phase variables [38]. Professional sports teams employ player profiling strategies to inform decision makers on player readiness, and injury risk [40]. Variations of countermovement jumps are commonly used as they are easy to use and sensitive to change [41,42].

Functional performance tests are useful for identifying physical limitations that may affect sports performance. For example, tests such as the drop vertical jump have been used to assess landing mechanics in anterior cruciate ligament reconstruction patients [43], while various single leg hopping tests have been used to assess performance in patients with ankle instability [33]. Functional performance tests that replicate elements of the athlete's activity are thought to be best [44]. Several tests such as the countermovement jump and squat jump have been incorporated by practitioners to assess the physical performance of ice hockey players [45,46]. However, propulsion in ice skating occurs by pushing laterally with the foot. In the vertical countermovement jump, the hip, knee and ankle all contribute to jump performance. However skating velocity is almost entirely determined by hip and knee motion, not ankle plantarflexion due to constraints of the skate [47]. Although the squat jump involves minimal stretch reflex, similar to ice skating [48], it too is performed in a vertical direction and therefore is not relevant to skating with its lateral push off [49].

Although there are many functional performance tests, it is unclear which test is best for measuring ice hockey skating performance.

The hockey stride can be described as having three distinct phases: the wind up, release and follow through [50]. Each stride begins with the wind up where the player's feet are directly underneath their hips in a V position with toes pointed approximately 45 degrees laterally. The V-shape allows the skate blade and lower leg to create a 45-degree angle relative to the ice. The release phase begins with the hips flexed 45 degrees and the torso flexed sixty degrees. The player releases the thrusting leg into a position of extension and abduction. Finally, the extension phase is a continuation of hip and knee extension. This final position causes valgus force at the knee and tibial external rotation [31]. This position is known as the position of no return for players returning from knee injuries as it places large valgus stress on the knee joint. In addition researchers have observed that this position of maximal extension while retaining contact with the ice was found to be the third most important factor in skating skill [50]. This position should be targeted in a structured rehabilitation program through specific neuromuscular control exercises that stimulate skating [31]. Therefore, the selection of functional performance tests requires careful consideration of player safety, sport specificity, biomechanical understanding, practicality and the athlete's current physical condition [51]. Construct validity and the degree to which a test measures what it proports to measure must also be addressed. Researchers and performance professionals must have a deep understanding of sport as construct validity is theory dependent [52]. A different, direction-specific testing approach is needed in ice hockey to address the distinct features that make the game different from land-based sports.

Interlimb asymmetry has been also investigated [55-59]. Researchers have highlighted that asymmetry greater than 15% may be associated with an increase of injury incidence compared to groups below that threshold [60-62]. The vast majority of asymmetry testing has examined field, and court-based athletes [55,56,58,63]. There are notable differences between field sports and ice hockey. Ice hockey is played on the ice, and therefore the minimal friction surface influences force production. Unlike field-based sports such as soccer that may have dominant limbs for activities like kicking, there does not appear to be a dominant leg for ice hockey players as they must push forcefully with both limbs to accelerate their center of mass. Amplified interlimb asymmetries occur in sports with preferred limb dominance [64]. Interlimb asymmetry calculations have been reported in elite youth soccer players [55,58], but asymmetry has not been reported in elite youth ice hockey players. Asymmetry has important implications for performance as the degree of asymmetry in the single leg, vertical countermovement jump was correlated with sprint times across distances of 5, 10 and 20 m in youth female soccer players [55]. Research with track and field athletes [65] shows performance drop-offs with larger interlimb asymmetries. However, in cycling [66] and American football [67] researchers observed that bilateral power deficits had no negative impact on performance. The research is variable with regards to interlimb asymmetry and may be sport dependent. Furthermore, asymmetry based on parameters such as distance and power may fail to capture subtleties of jump strategy [77]. These measurements have not been reported in ice hockey and may serve as functional baselines for comparison among multiple age groups.

Finally, normative data has been useful for providing age and sex specific reference values for jumps [68], functional movement [69], kinematics [70], and asymmetry [71]. A large study conducted investigating the age, sex and activity level on countermovement jump performance in both children and adolescents observed that jump height increased significantly with increasing age [73]. This study provides researchers and practitioners with data to be used as normative references. Normative data has also been collected by researchers investigating age and sex specific performance of the standing long jump for school children aged 9-18 [68], countermovement jump landing kinematics for both adolescent girls and boys [70], and to assess the side jump height differences during the single-leg vertical jump in men and women [71] . In addition, normative values have been reported in other populations including the US military for parameters such as power, balance, flexibility, and functional movement [74]. Normative values are important so that other researchers and coaches can gauge their current players' performance. They may also be used to assess progress from structured strength and conditioning programs [75]. Jump parameters may be measured as means of documenting performance throughout the season. However, these measurements have not been assessed for elite youth ice hockey players.

Specifically, to the author's knowledge, there are no normative reference values in elite youth ice hockey.

1.1 Overall Purpose

The first objective of this thesis is to systematically review the literature to determine which injuries are most common in ice hockey, and to describe the injury rates. This review focuses on players 16 years of age and older playing junior, collegiate and professional hockey as bodychecking has already been introduced (U13 Hockey Canada, U12 USA Hockey), removing it as a confounding factor [76]. Given the unique biomechanics of skating, and the specific injury profile for injuries in ice hockey, a specific performance test should be identified to evaluate performance. The second objective of this thesis is to identify which performance test is most appropriate for elite youth ice hockey players, to define meaningful parameters to describe the performance, and to evaluate these parameters in order to develop a subset of reliable and independent parameters. The third objective of this thesis is to describe the normative values for these parameters for a range of youth player ages that may be used for reference by researchers and performance professionals. Together, these objectives achieve three projects: investigating injury rates in elite ice hockey, calculating the reliability of the single leg, medial countermovement jump parameters, and describing normative values for these parameters for players between 10U and 18U age groups. Each of these objectives were addressed in individual chapters in this thesis.

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Chapter 2

2 What is Injury in Ice Hockey: An Integrative Literature Review on Injury Rates, Injury Definition, and Athlete Exposure in Men's Elite Ice Hockey

A version of this manuscript has been published in the journal Sports.

2.1 Introduction

Ice hockey is a high intensity sport where players can reach speeds of up to 48 kph [1]. These speeds, and the nature of collision sports lead to musculoskeletal injuries at all levels of ice hockey [1-3]. There is a need to accurately quantify injury rates in men's elite ice hockey both for assessing player risk [4] and the associated economic burden [5]. Injury rates in ice hockey have been investigated in order to assess injury trends, injury types, injury location, and underlying injury mechanisms [6]. Injury rates can also be used to quantify the effects of rule changes [7]. Accurate data is needed in order to better investigate areas of concern while objectifying the effects of rule changes and other preventative measures [8,9].

Differences in the definitions for injury and athlete exposure (AE) lead to inconsistencies between studies and obscure the resulting injury rates. Consensus statements on injury definitions and data collection procedures have been developed for soccer [10] and rugby [11], but have not been developed for ice hockey. Consistent definitions and methods to evaluate ice hockey injuries are required [12] to improve the comparability of published data [8]. Our objective was to review musculoskeletal injury rates in men's elite ice hockey, as well as definitions of injury and athlete exposure. We focused on elite players aged 16 years and older playing junior hockey (United States Hockey League, North American Hockey League, Canadian Hockey League), US and Canadian College Hockey (NCAA Div. 1 and Div. III, Canadian Inter-University Sport), international or minor professional and professional hockey (Finnish Elite League, Swedish Elite League, Japanese Elite League, International Ice Hockey and the National Hockey League) as this cohort has not been as extensively studied as other levels such as high school and youth hockey [13,14]. In addition, injury rates in ice hockey increase with the introduction to body checking which occurs at later ages [15]. Finally, the economic burden of injury at this level is high. During two seasons in the National Hockey League (NHL), injuries represented a total salary cost of US $218 million per year. While salary losses represent a significant financial burden, it is hoped that improved injury surveillance will reduce these costs.

2.2 Methods

We conducted an integrative literature review to evaluate musculoskeletal injury rates, injury definition and athlete exposure measurement in elite ice hockey, using a published review framework [16]. We formulated four research questions a priori to focus our review: What is the rate of musculoskeletal injuries in men's elite ice hockey? In elite ice hockey, what injury definition is best suited to enable direct comparisons among research studies? In elite ice hockey, what measure of athlete exposure is best suited to achieve consistent and comparable injury rates? What are the common lower-extremity injury types in men's elite ice hockey?

Literature Search

A PubMed search strategy was created with the assistance of a University research librarian. PubMed was chosen as a search engine as it is the optimal tool in life sciences and biomedicine [17]. The literature search was performed May 9-10, 2019. The search strategy used the key words: hockey AND (injury OR injuries) AND (NHL OR national OR international OR world OR competitive OR professional OR elite OR high caliber OR high caliber OR collegiate OR university OR intercollegiate OR NCAA OR "National Collegiate Athletic Association"). In addition, the same search strategy was performed on SPORTDiscus. The PubMed and SPORTDiscus records of these references were pooled and screened based on established inclusion and exclusion criteria (Table 1). Articles that were not relevant to our research questions were excluded. The references in the remaining papers were reviewed to identify additional relevant articles. All studies were reviewed by both authors for their relevance to the four research questions.

Original, peer-reviewed, English language research articles evaluating the injury rates in elite ice hockey were included. Editorials, abstracts, books, excerpts from conference proceedings and unpublished data were excluded. Articles were also excluded if they did not contain information related to one or more of the following variables: injury definition, injury rate, athlete exposure, or injury location.

Table 2.1 Inclusion/exclusion criteria for literature search.

Title	Inclusion Criteria	Exclusion Criteria	Rationale for This Criterion
Publication Type	Peer-reviewed original research articles only	Review papers, non-peer reviewed articles, editorials, abstracts, book chapters and conference proceedings	For practical reasons, it was deemed to exclusively review primary research articles, rather than non-peer reviewed or abbreviated sources.
Language	English language	Non-English	For practical reasons, it was deemed acceptable to only include studies published in English.
Publication Date	November 1976 to April 2019	Publications prior to November 1976	The characteristics of ice hockey injury reporting may change over time due to rule changes, technological advancements and education. Literature was captured backdated to 1988 to capture these potential developments.
Study Design	Multi-center studies, randomized control trials, cohort studies, case-controlled studies and cross-sectional studies.	Case studies	Study design was chosen to ensure reasonable empirical support, and high methodological rigor in defining injury and injury rates amongst competitive hockey players.
Gender and Age	Men athletes aged > 16-years participating in a competitive league/team	Women only studies or men ages < 16, age unspecified involved in youth sport	The primary outcome of interest was injury definition and injury rate calculation in competitive ice hockey played by men. Studies that compared rates between males and females and have separate data for both genders were also included for baseline comparisons. Men athletes aged > 16 were considered appropriate. This age demographic represents elite players.
Playing Level	Competitive participation	Recreational sport/training	The primary outcomes of interest are injury definition, injury rates, mechanism and anatomical location sustained during competitive ice hockey.
Sport	Injuries must be sustained during ice hockey games and practices	Any sport other than ice hockey	Sports included other than ice hockey may result in definitions, and injury rates that are too broad.
Types of Injury	Injuries to the musculoskeletal system, including strains, sprains, breaks	Concussions, spinal injuries, head/face, lacerations	The primary outcomes of interest are soft tissue injuries of the upper and lower extremity during competitive ice hockey
Outcome Measures	Injury definition, injury rates, athlete exposure, mechanisms, anatomical location	Outcomes other than injury definition, injury rate, and athlete exposure, mechanisms and anatomical location	The primary outcomes of interest are injury definition, injury rates, mechanisms and anatomical location.

2.3 Results

The PubMed and SPORTDiscus searches identified 2463 references. An additional 3 pertinent articles were identified from the references from these articles. A total of 2212 articles were vetted after 254 duplicate articles were removed. Two-thousand, one-hundred and eighty-four of these articles were excluded as they were not relevant to any of our four research questions. No relevant articles were published prior to 1975. Accordingly, a total of

28 articles were included. The flowchart describing the process for selecting relevant studies is presented in Figure 1.

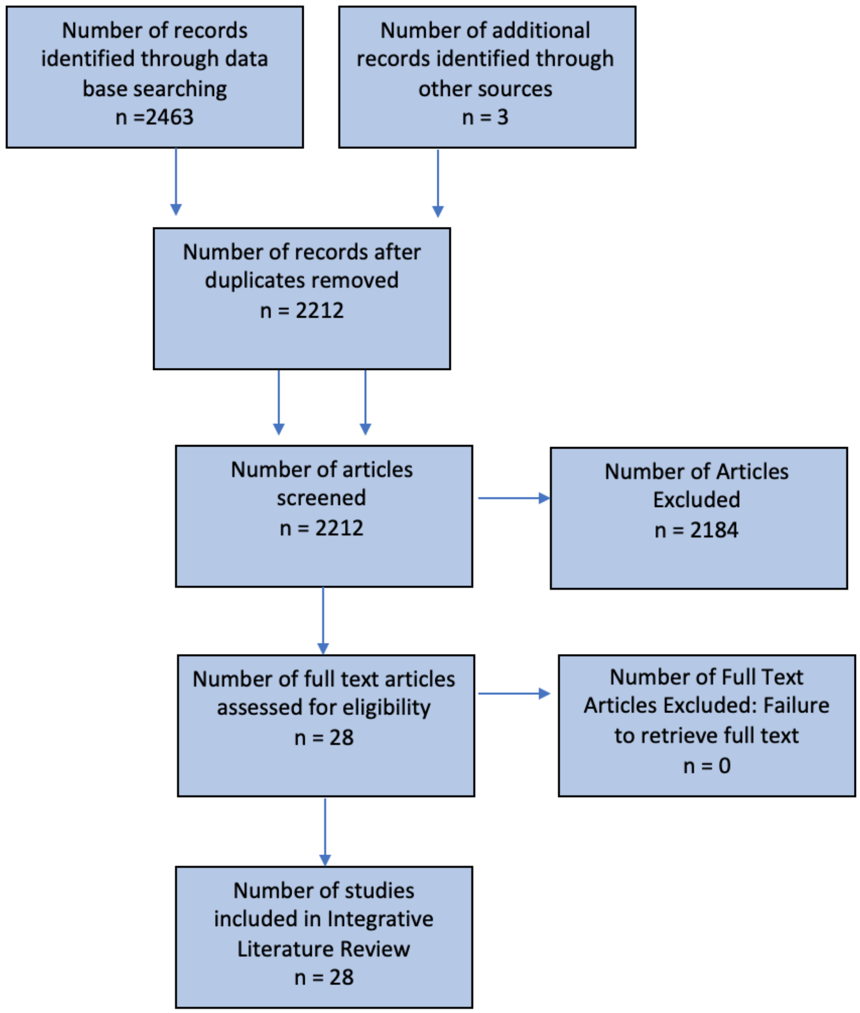

Figure 2.1 Flowchart describing the process for selecting relevant studies. The top row represents the identification process. The second and third rows represent the screening process. The fourth row represents the eligibility of the articles assessed and the last row identifies the articles included.

2.3.1 Rate of Musculoskeletal Injuries in Men's Elite Ice Hockey (Question #1)

Injury rate data, and study design characteristics are presented for each of the 24 studies in Table 2. Injury rates in competitive ice hockey range from 13.8 to 121/1000 player-game hours, depending on factors such as the league of play and exposure estimate. Professional players in Europe and North America experience musculoskeletal injury rates between 49 to

80/1000 AE as measured in player-game hours [4,18] while the collegiate hockey players in Canada and the United States experience lower rates (13.8 to 19.95/1000 AE) as measured in player games [19,20]. The highest injury rates are experienced at the junior level (39.8 to 121/1000 player-game hours) [21,22]. The majority of these musculoskeletal injuries are attributed to collision with other players, the boards or the hockey puck [18,20,23,24].

Table 2.2 Summary of papers evaluating injury definition, injury rate, athlete exposure and injury mechanism in men's elite ice hockey.

Authors	Year	Demographic	Injury Definition	Type	Injury Rate	Mechanism of Injury	Injury Type	Injury Rate Computation
Hayes [25]	1975	Intercollegiate Ice hockey	"An event requiring some attention by the team trainer or physician or both."	Medical Attention	1.14 injuries per game (Canada) 1.28 injuries per game (USA)	Collision	Head and face, knee, shoulders	Total injuries/Total number of games
Sutherland [26]	1976	Youth-Pro	The injuries were classified according to the standard nomenclature of athletic injuries as recommended by the American Medical Association	N/A	Pro Group: 143/1000 AE (practice and games)	N/A	Scalp and face 60.8%, Groin 9.1%, knee 7.8%, shoulder 5.9%	N/A
Hayes [27]	1978	Youth-Pro	"Any change in the normal, healthy state of the individual that requires medical attention and disables a player either temporarily or permanently."	Medical Attention	University: 1.17/Game Professional: 1.15/Game	Stick and puck contact	Contusions and lacerations	Total injuries/Total number of games
Rielly [28]	1982	College Hockey	"A reportable injury was defined as being one that required definitive physical evaluation and medical treatment."	Medical Attention Definition	1/12.7 h of play **	Player contact (43.3%), puck contact 27%	Face, hips, shoulders	N/A
Meeuwisse et al.	1988	Canadian University	Injury was defined as any disability arising either in practice or competition that required physical attention.	Medical Attention Definition	As calculated by percentage. Hockey had the greatest	N/A	Knee, ribs, low back	N/A

[29]					percentage of players injured.			
Lorenzton, Wedren, Pietila [30]	1988	Swedish Elite Team	"Injury was defined as any injury occurring during on-ice practice or games and causing the player to miss the next practice session or game. Facial lacerations, which are common in ice hockey but do not cause absence from practice or game are reported separately."	Time Loss Definition	78.4/1000 player game hours, 1.4/1000 player practice hours	Checking 32.9%, Player contact 25%, Puck contact 14.5%, stick contact 11.8%, collision with boards 6.6%, cutting, 6.6%, skate contact 2.6%	Contusions, strains and sprains were the most common types of injury. Knees were the most commonly injured joint (5 injuries were complete tears of the MCL). 53.7% of injuries were localized in the lower limb.	Practice Injury Rate = number of injuries/Practice Hours × Roster (23.4). Games Injury Rate = number of injuries/Game hours × Total Players on ice (6).
Lorenzton, Wedren, Pietila, Gustavsson [18]	1988	Swedish National Team (40 International games)	"Injury was defined as any injury occurring during games and causing the player to miss the next practice session or game. Facial lacerations, which are common in ice hockey but do not cause absence from practice or game are reported separately."	Time Loss Definition	79.2/1000 player game hours	Player contact 42.1%, checking 31.6%, collision with boards 10.5%, puck/skate contact 5.3%	Contusions, strains and sprains were the most common types of injury. Knees were the most commonly injured joint, followed by the thigh and wrist.	Total Injuries/Total AE × 1000; Total AE = games × Total players on ice (6)
Tegner, Lorentzon [24]	1991	Swedish Elite League (12 teams)	"Injury was defined as any injury occurring during ice practices or games and causing the player to stop playing or to miss the next practice session or game. Facial lacerations,	Time Loss Definition	53/1000 player game hours (76% of injuries occurred during games)	Stick contact 25.5%, player contact 24%, puck contact 11.2%, collision	Strain, laceration and contusions were the most common types of injury. Knees were the most common joint	Total Injuries/Total AE × 1000

			which are common in ice hockey, but do not cause absence from practice or games, are also reported.”			with boards or goal posts 9.7%	injured (13.2%), followed by the hip (12.1%)	Total AE = games × Total players on ice (6)
McKnight, Ferrara, Czerwinska [23]	1992	Collegiate (Div. I)	(1). Loss of practice or game time because of injury/illness, (2). Injury that required sutures even if no time loss was involved, (3). Injury in which a fracture or dislocation/subluxation occurred even if the athlete was able to continue participation	Time Loss/Medical Attention Definition	Total: 10.22/1000 AE Games: 14.73/1000 game hours. Practice: 2.52/1000 practice hours	Person/Ice Impact 42%, impact with the boards 32%. The shoulder and knee had the highest rate of injury when compared to other body parts	Contusions and strains were the most common types of injury	number of Injuries/Total AE × 1000 (games and practice)
Pelletier, Montelpare, Stark [20]	1993	Canadian Inter-collegiate	“Any brain concussion causing cessation of the athlete’s participation for physical observation before return to play, any dental injury requiring professional attention, any injury/illness causing cessation of an athlete’s customary participation throughout the participation day following day of onset, or any injury/illness requiring substantive professional attention before the athlete’s return to competition.”	Time Loss/Medical Attention Definition	19.95/1000 AE (player games)	Body checking 44.6%, collision (accidental) 28.8%, stick 12.2%, fighting 6.5%, illegal body check 5.8%, non-contact 2.2%	Sprains (31%) and contusions (21%) were the most common type of injury. Knees were most frequently injured (18.6%), followed by teeth and eyes (17.6%), and shoulders (14.9%),	Total Injuries/Total AE × 1000 Total AE = games × Total players on team (19)
Pettersson, Lorentzon [31]	1993	Swedish Elite League	“Injury was defined as any injury occurring during on-ice practice or games and requiring medical attention and treatment. Injuries causing the player to miss the next practice or game have been analyzed separately.”	Medical Attention Definition	74.1/1000 game hours	Stick contact 26.1%, player contact 23.9%, puck contact 16%, collision with boards 7.2%,	Contusions, lacerations, sprains and strains are the most common mechanisms of injury. Knees were the most common joint injured followed by the thigh, groin and shoulder	Total Injuries/Total AE × 1000 Total AE = games × Total players on ice (6)

						fall (no contact) 4%		
Stuart, Smith [21]	1995	United States Hockey League	"Injury was defined as an event that kept a player out of practice or competition for 24 h, required the attention of a team physician (e.g., suturing lacerations) and included all dental, eye and nerve injuries and concussions."	Time Loss/Medical Attention Definition	Overall injury rate was 9.4/1000 player hours, game injury rate was 96.1/1000 player hours, practice injury rate was 3.9/1000 player hours	Collision 51%, stick contact 14%, skate/puck contact 11%, off-ice injuries 8%	Strains, lacerations and contusions were most common mechanism. Aside from the face, the shoulder, hip, lumbar spine and knee were the most common anatomical sites of injury	Total Injury/AE × 1000 = Practice Injury Rate; Practice AE = Practice Hours × Roster (25) Total injuries/Total AE × 1000; Total AE = number of games × Total players on ice (6)
Cunningham [32]	1996	University Games	"A recordable injury was defined as any incident occurring during warm-up or competition and which required medical attention, on-field management to enable continued participation, or removal from the playing field."	Medical Attention	33.5% of injuries in relation to total number playing the sport	Player collision	Muscle strains and hematoma (21.7%)	Number of injuries/number of players participating
Molsa, Airaksinen, Nasman, Torstila [33]	1997	Finnish National League, Finnish First Division	"An injury was defined as any trauma occurring during practices or games and causing absence from the next practice or game or needing treatment (ex. stitches), examination by a physician (ex. radiographs), or rehabilitation prescribed by a physician (ex. physical therapy). Injuries due to overuse were excluded."	Time Loss/Medical Attention Definition	66/1000 player-game hours, 36/1000 player game hours (Div. I)	Checking 29.7%, stick 14.6%, contact with opponent 14.6%, puck 7.9%	Contusions, strains and sprains were the most common type of injury, the knee joint and groin were the most common locations	Total Injury/AE × 1000 = Practice Injury Rate Practice AE = Practice Hours × Roster (21) Total Injuries/Total AE × 1000; Total AE = number of games × Total players on ice (6)

Pinto, Kuhn, Greenfield, Hawkins [34]	1999	Junior A Hokey Players (22 players)	"An injury was defined as any event that required the attention of a physician or trainer."	Medical Attention Definition	121/1000 player game hours	Contact with stick 16.2%, overuse 13.5%	Sprains/subluxations/dislocations were the most common, aside from the face, the shoulder and knee were the most common	Total Injury/AE × 1000 = Practice Injury Rate; Practice AE = Practice Hours x Roster (22) Total Injuries/Total AE x1000 Total AE = #games × Total players on ice (6)
Molsa, Kujala, Nasman, Lehtipuu, Airaksinen [35]	2000	Finnish Elite League (7 teams, 3 different decades)	"An injury was defined as any sudden trauma occurring during practice or game that led to examination and treatment by a physician." Minor injuries requiring no absence were also included, but minor injuries needing no medical care and injuries due to overuse were excluded	Medical Attention Definition	Game injury rate increased from 54/1000 player hours in the 70's to 83/1000 player hours in the 90's, most common mechanism was collision	Checking, stick, falling, collision with opponent, puck, collision with boards	Contusions, sprains/strains and lacerations were the most common mechanisms of injury. The knee was the most common major injury of the lower quadrant	Player years of exposure, (Seasons × Teams × Players) × Practice Hours x Roster = Practice Injury Rate: Player years of exposure, (Seasons × Teams × Players) × Game Hours × Roster (6) = Game Injury Rate.
Flik, Lyman, Marx, [19]	2005	American Men's Collegiate Ice Hockey (8 teams/1 season)	"An injury was defined specifically as any injurious episode that led to loss of participation in the immediate subsequent AE, whether it was a practice or game."	Time Loss Definition	Overall injury rate was 4.9/1000 AE, 13.8/1000 AE games, 2.2/1000 AE practice	Collision with opponent 32.8%, collision with boards 18.6%, overuse 8%, puck 6.2%	Concussions were the most common, followed by knee (MCL) and shoulder injuries	Total Injury/AE × 1000 = Practice Injury Rate Practice AE = Practice Hours × Roster Est Total Injuries/Total AE × 1000; Total AE = number of games × Total

								player avg attendance
Agel, Dompier, Dick, Marshall [36]	2007	NCAA Men's Ice Hockey (16 years of data: Div. I-III)	"A reportable injury in the ISS was defined as one that (1) occurred as a result of participation in an organized intercollegiate practice or competition and (2) required medical attention by a team certified athletic trainer or physician and (3) resulted in restriction of the student-athlete's participation or performance for 1 or more calendar days beyond the day of injury. The injury definition was expanded in the '94–95' academic year to include any dental injury occurring in an organized practice or game, regardless of time lost."	Time Loss Definition	16.27/1000 AE games, 1.96/1000 AE practice	Player contact 50%, other contact 39.6%, no contact 9.7% (game numbers). Injury was 8x higher in games.	Knee internal derangement (13.5%) was the most common lower extremity injury reported during games, followed by concussions and AC injuries. Whereas pelvis and hip strains (13.1%) were the most common injury reported at practice.	Total Injury/AE × 1000 = Practice Injury Rate; Practice AE = Practice Hours × Roster (26) Total Injuries/Total AE × 1000 Total AE = number of games × Total players (19)
Rishiraj, Lloyd-Smith, Lorenz, Michel [37]	2009	Men's Varsity Ice Hockey (Canada)	"Any event, during team or team related game, practice, and/or activity (on or off the ice), requiring any attention by the team's therapist and/or physician and subsequent game and/or practice time loss."	Time Loss Definition	3.7/1000 player game and practice exposure	Non-contact, ice/board contact, body contact	Sprains 20%, strains 20%, concussions 13% and contusions 12%	Total Injury/AE × 1000; Practice AE = Practice Hours × Roster Total Injuries/Total AE x1000 Total AE = number of games × Roster Selected
Kuzuhara, Shimamoto, Mase [38]	2009	Japanese Elite Team	"An injury was defined as any event that occurred during on-ice practices or games that required medical attention and treatment."	Medical Attention Definition	74.3/1000 player game hours, 11.7/1000 player-game hours for injuries resulting in any time loss, 11.2/1000 player-practice hours, 1.1/1000 player-practice hours for	Overuse 52%, puck contact 21%, stick contact 15%,	Contusions 35.4%, strains 15.6%, lacerations 9.3%	Overall injury rate (regardless of time loss): #of injuries/number of hours per 1000 player-hours number of injuries causing time loss (>1 day)/number of

					injuries resulting in any time loss	falling 12%		hours per 1000 player-hours Number of player: 2003 (20 players/game, 25 players/practice), 2004 (20 players/game, 37players/practice), 2005 (22 players/game, 32 players/practice)
Agel, Harvey [39]	2010	NCAA Men's and Women's Ice Hockey (Div. I and III)	Same as Dick et al. above	Time Loss Definition	18.69/1000 AE games, 2.23/1000 AE practice for men, 12.10/1000 AE games, 2.90/1000 AE practice for women	Player contact 48%	The most common injury among men was concussion followed by shoulder and knee ligamentous in juries	Number of Injuries/Number of AE (games or practice × roster) × 1000
Engebretsen, Steffen, Alonso, Dvorak, Junge, Meeuwisse, Mountjoy, Renstrom, Wlikinson [40]	2010	Olympic Sport	"An athlete was defined as injured or ill if he/she received medical attention regardless of the consequences with respect to absence from competition or training."	Medical Attention Definition	A total injury rate of 111.8/1000 AE was reported for both males and females. A total of 276 males were registered with 44 total injuries (16%) in men's elite ice hockey.	N/A	N/A	Number of Injuries/Athlete Exposure
Kerr, Dompier, Snook, Marshall, Klossner, Hainline, Corlette [41]	2014	NCAA Sports	"Any injury occurring during an organized intercollegiate practice or game." (1982) "A reportable injury was defined as an injury that (1) occurred as a result of participation in an organized intercollegiate practice or competition, (2) required attention from an AT or physician, and (3) resulted in restriction of the student-	Time Loss/Medical Attention Definition	N/A	N/A	N/A	Number of Injuries/AE (average team roster) × 1000

			athlete's participation for 1 or more days beyond the day of injury." Multiple injuries from one event could be included. In addition, AT's were asked to include any dental injuries that occurred in an organized practice or game, regardless of time lost. 2003-onward). Beginning in 2009–2010 academic year, non-time loss injuries were also monitored.					
McKay, Tufts, Shaffer, Meeuwisse [4]	2014	NHL Players (2006–2012)	"Any event captured by the IIE form, and restricted to those designated as practice-related or game related, resulting in one or more-man games lost.	Time Loss Definition	15.6/1000 AE based on estimated AE's. Based on recorded TOI *, the injury rates were roughly threefold higher at 49.4/1000 player-game hours	Body checking was the most common mechanism	Most commonly injured body regions were the head (16.8%), thigh (14%), and knee (13%)	Estimated AEs = 82 games × 19 players (including goalie) TOI (NHL.com) = number of injury events/sum of individual AE time
Tuominen, Stuart, Aubry, Kannus Parkkari [42]	2015	Men's International Ice Hockey (2006–2013)	"The definition of an injury was made in accordance with the accepted international ice hockey norms: (1) Any injury sustained in a practice or a game that prevented the player from returning to the same practice or game, (2) any injury sustained in a practice or a game that caused the player to miss a subsequent practice or game, (3) a laceration that required medical attention, (4) all dental injuries, (5) all concussions, (6) all fractures	Time Loss/Medical Attention Definition	14.2/1000 AE player games, 52.1/1000 AE player game hours For WC A-pool tournaments and Olympic games the injury rate was 16.3/1000 player-games, 69.6/1000 player-game hours	Body contact and puck contact were the mechanisms	Most common types of injuries were lacerations, sprains, strains, and contusions. The knee was the most commonly injured lower body segment, MCL was the most common, and the shoulder was the most common site of an upper body injury.	Player game injury rate (based on 22 players on each team): Number of injuries/number of players (two teams)/number of games × 1000, Player game-hour injury rate (based on 6 players on ice at once): number of injuries/number of players on ice at the same time (two teams)/number of games × 1000

Kerr et al. [43]	2015	NCAA Ice Hockey	Injuries were defined as those that occurred in an organized NCAA-approved practice or competition and required medical attention by a physician or athletic trainer. An athlete-exposure was defined as one student-athlete's participation in one practice or one competition.	Medical Attention Definition	9.5/1000 AE	N/A	Concussions, contusions, fractures	Number of Injuries/Number of Athlete Exposures
Tuominen, Stuart, Aubry, Kannus, Parkkari [22]	2016	World Junior Hockey Players (ages 18–20)	"The definition of an injury was made in accordance with the accepted international ice hockey norms: (1) Any injury sustained in a practice or a game that prevented the player from returning to the same practice or game, (2) any injury sustained in a practice or a game that caused the player to miss a subsequent practice or game, (3) a laceration that required medical attention, (4) all dental injuries, (5) all concussions, (6) all fractures	Time Loss/Medical Attention Definition	11/1000 AE player-games, 39.8/1000 player-game hours	Body checking 32%, stick 13%, and puck contact 13%	The knee was the most frequent site of lower body injury in WJ and U20 tournaments (33%), MCL sprain was most common, the shoulder was the most common upper body injury.	Player game injury rate (based on 20–22 players on each team): number of injuries/number of players (two teams)/number of games × 1000, Player game-hour injury rate (based on 6 players on ice at once): number of injuries/number of players on ice at the same time (two teams)/number of games × 1000
Lynall, Mihalik, Pierpoint, Currie, Knowles, Wasserman, Dompier, Comstock, Marshall, Kerr [44]	2018	Collegiate Men's and Women's Hockey (2004–2005, 2013–2014)	"An injury that (1) occurred as a result of participation in an organized practice or competition; (2) required medical attention by a certified AT or physician; and (3) resulted in restriction of the student-athlete's participation for 1 or more days beyond the day of injury. Since the 2007–2008 academic year, HS RIO has also captured all concussions, fractures, and dental injuries, regardless of time loss." "Beginning in the 2009–2010 academic year, the NCAA-ISP also	Medical Attention/Time Loss Definition	Collegiate Men: 13.45/1000 AE	Collision	Strains/Sprains	Total Injuries/Total Athlete Exposure

	began to monitor all non–time-loss injuries. A non–time-loss injury was defined as any injury that was evaluated or treated (or both) by an AT or physician but did not result in restriction from participation beyond the day of injury.”	

TOI * = Time on Ice. ** = Author did not specify how injury rate was calculated.

The injury rates in practice are much lower than games. Practice rates range between 1.4/1000 player-practice hours for Swedish Elite hockey [30] to 3.9/1000 player-practice hours for junior hockey [21], versus game injury rates of 74.3/1000 player-game hours [38] and 121/1000 player-game hours [34], respectively. Although the injury rates are lower for practices, the number of hours spent in practices is several-fold greater than games, so the actual number of injuries is higher than indicated by the injury rate.

Several long-term studies have assessed patterns in injury rates over time. For example, injury rates in the Finnish Elite League have increased from the 1970s (54/1000 AE) to the 1990s (83/1000 AE) using the player-game hours exposure estimate [20 years: 35]. Overall game injury rates increased 1.8% annually over a seven-year period (2000–2007) in men's NCAA ice hockey using the player game estimate. Practice rates also increased 7.8% annually during this time [39]. In contrast, on average, injury rates have decreased between 2007 and 2013 in men's International Ice Hockey Federation World Championship tournaments [42] (6-years). One Canadian Intercollegiate team also experienced decreases in injury rate over a six-year period from 11.3 to 8.30/1000 player games (1991–1996) [6-years: 37].

There was a large variance in injury rates between studies. This large variance is a function of variability in the definitions for both injury and athlete exposure. As noted in previous papers, establishing consistent definitions of injury and athlete exposure are important first steps for objectifying injury risks in high caliber ice hockey [10,45].

2.3.2 Injury Definition in Men's Elite Ice Hockey (Question #2)

Probably the most important methodological factor affecting injury rate calculations is the definition of what constitutes an injury [45]. A review investigating the methods of data collection on injury surveillance identified three categories of injury definitions [45]. Category 1 defines injuries as all complaints regardless of time loss. All injuries are recorded, regardless of the severity or amount of time lost from competition. Category 2 defines injuries as events that require medical attention by a member of the medical staff. Therefore, according to this definition, a member of the medical staff, typically a team therapist or team doctor, must diagnose the injury. Finally, category 3 defines injuries as events that have a time loss element. Accordingly, an injury is only recorded if the athlete misses a team-related practice or competition. Individual studies typically fit into one, or more of these categories.

Our review identified 28 studies evaluating injuries in elite ice hockey. Early research investigating injury rates in the Swedish Elite League, and the Swedish National team used the time loss definition of injury (Category 3). As shown in Table 2, the majority of ice hockey injuries studies use either a time loss (Category 3) or medical attention definition (Category 2). None of the articles evaluating injuries in elite ice hockey used the all complaints definition (Category 1).

Our review found inconsistent definitions of a reportable injury in ice hockey research based on the time loss definition. In addition, the list of injuries has expanded over time. Facial lacerations were considered reportable injuries in 1991 [24], while sutures, fractures, dislocations and subluxations were added in 1992 [23]. Concussions, dental and eye injuries were added in subsequent years [20,21], potentially increasing injury rates by expanding the list of injuries. In addition, illness may be counted as an injury, inflating the injury rates [23].

The definition of injury based on medical attention (Category 2) has also been used to quantify competitive ice hockey injury rates [31,34,38]. However, this metric is often combined with the time loss component to result in a broader interpretation of injuries [20-23,35,46]. For example, injuries such as concussions, dental injuries, lacerations and eye injuries are captured with medical attention by a team physician or athletic trainer, resulting in a more extensive list of ice hockey related injuries compared to definitions that did not include these injuries [45]. Of note, some studies have expanded their list to include illnesses and psychological complaints that are unrelated to injury [47].

The time loss definition (Category 3) is the easiest to use as it is easy to track time loss. However, it leads to the fewest reported incidents [45] as it fails to capture the athletes that continue to train and play while injured [48]. Depending on the time of year, some injuries may be under reported as injured players continue to play throughout key time periods, such as playoffs. The medical attention definition (Category 2), though broader and encompassing a greater number of conditions, also has limitations. The subjective interpretation of what constitutes medical attention may lead to systemic bias [49], and the types of injuries managed by the various practitioners may differ based on their qualifications and status [45].

2.3.3 Athlete Exposure Metric in Men's Elite Ice Hockey (Question #3)

Athlete exposure is the second component of injury rate. An athlete exposure is defined as one athlete participating in a practice or game in which there is a potential for athletic injury [50]. Injury rates are typically based on 1000 athlete exposures. These exposure rates can be quantified as injuries per 1000 game-hours (or injuries per 1000 games), injuries per 1000 practice-hours, or overall injuries per 1000 AEs (games and practices combined). Injury per 1000 player-game hours is based on a 60-min active game and is calculated as the number of injuries/number of players on the ice at the same time (6)/number of games × 1000. Many researchers use this method [18,21,24,30,31,33,34]. However, this exposure estimate is not used consistently among researchers. For example, several studies accounted for both teams when calculating athlete exposure (number of injuries/number of players on ice at the same time (two teams)/number of games × 1000 [22,42]. In contrast, another study used a 20 person roster, including the back-up goaltender, to calculate athlete exposure per 1000 player-game hours [38]. This larger number of players will lead to a smaller injury rate.

Our review identified different nomenclatures pertaining to the athlete exposure metric, such as player-games and player-game hours [42]. The number of athletes used to quantify these exposure rates vary between studies, and are not consistently defined. For example, one researcher [42] calculated player-game injury rates based on 22 players competing for each team in a game (i.e., 44 players) while another [30] calculated player-game hours injury rates based on 6 players. This was based on the number of players on the ice at a time, and whether goaltenders were included. Other researchers have used roster averages over a set period of time [36,37], or a tournament [22,42] to calculate player-game injury rates.

Injury per 1000 games is the average number of injuries that one player experiences per 1000 games (number of injuries/total number of players (roster)/number of games × 1000 [20,37]. Our review found different implementations of this approach as there was some research that counted both rosters when computing athlete exposure [42]. This has an effect on total estimated exposures and can lead to reduced injury rates. Finally, several articles did not fully describe whether they included both rosters or a single team roster when calculating athlete exposures [19,23], making it difficult to determine accurate injury rates.

In addition, we investigated the impact of calculating injury rate based on the actual time on ice (TOI) [4,51]. Using the actual time on ice, injury rate was calculated as the number of injury events/sum of individual AE time as found on the player statistics page (www.nhl.com/stats/player). The time on ice was calculated based on the number of minutes and seconds that each individual played per game over the season. The difference between estimated athlete exposure (number of injuries/number of teams (30)/number of players on roster each game (19)/number of games (82)) and the TOI metric was large. As much as three times the amount of exposure was identified by estimating exposure rates. However, when comparing the time on ice metric to the estimated player game-hour metric, the differences were minimal. The player game-hour exposure (based on one hour per game rather than the actual amount of time that players spent on ice, which changes due to overtime periods and penalties) is similar to the time on ice calculations (14,676.2 h calculated as the sum of players' time on ice versus 14,760 h calculated as 30 teams × 82 games × 6 players) [4].

Our review found that practice athlete exposure was calculated consistently in most studies. Injury per 1000 practice hours (number of injuries/number of practice hours/number of players on team × 1000) was the standard [21,30,33,34].

2.3.4 Lower-extremity injury type in men's elite ice hockey? (Question #4)

Our review identified five studies focusing on specific anatomical areas prone to injury in high caliber ice hockey (Table 3). The knee was the most common lower body injury site [18,20,22,24,26,30,31], and the medial collateral ligament (MCL) was the most frequently injured ligament [19,20,24,36,37]. One study examined the incidence and injury characteristics in Collegiate hockey players playing on one team over an eight year period and found 13 MCL injuries [52]. Seventy-seven percent of these MCL injuries were attributed to player collision [52]. MCL game injury rates in collegiate hockey were

1.47/1000 AE, and practice rates were 0.13/1000 AE [52]. Although less common, anterior cruciate ligament (ACL) injuries also occur during ice hockey [53]. Over a ten year period researchers observed an ACL injury rate of 0.42/1000 AE in National Hockey League players [51]. Intentional body contact attributed to 40.3% of all ACL injuries during play, and 25.4% occurred as a consequence of incidental contact [51]. Finally, hip and groin injuries are also prevalent during games [54-56]. Groin and abdominal strain rates in the NHL increased from 0.81 to 1.13/1000 AE from 1995-1997 with 69.12 % of these injuries occurring due to contact [55]. Using publicly available data from the NHL website, researchers observed that the intra-articular hip injury rate was 1.81/1000 AE, with labral tears accounting for 69.1% of these injuries. The next most prevalent injuries were osteoarthritis, hip loose body and femoacetabular impingement (FAI) [56]. The injury rates for hip and groin injuries were similar when compared to the NCAA (1.03/1000 AE), with strains of the hip and groin accounting for 67.2% of these injuries, followed by contusions (16.9%) [54]. However, these numbers are confounded as they may reflect differences in the definition of injury and athlete exposure.

Table 2.3 Lower-Extremity Injury types.

Authors	Year	Demographic	Injury Definition	Type	Injury Rate	Mechanism of Injury	Injury Type	Injury Rate Computation
Emery, Meeuwisse, Powell [55]	1999	National Hockey League	"Any injury recorded as a muscle strain injury in any of the hip flexor, adductor and abdominal muscle group. Femoral, inguinal and abdominal hernias were also included in this group."	Time Loss Definition	95-'96: 0.81/1000 AE '96-'97: 1.13/1000 AE	34.56% with contact, 30.88% with no contact, 34.56% with unknown contact	groin/abdomina l	Total # of injuries per 1000 AE (practice or games)
Epstein, Mchugh, Yorio, Neri [56]	2013	National Hockey League	"Players who sustained an intra-articular hip injury were further classified based on the diagnosis of a hip labral tear, FAI, osteoarthritis, chondromalacia, loose body, or other hip injury."	N/A	1.81/1000 player game hours (for all positions)	Labral tear 69.1%, osteoarthritis 13.8%, hip loose body 6.3%, FAI 5.3%	Intra-articular hip injury	Using publicly available data from the NHL website, total time on ice and total game hours played by each position player per season were calculated
Grant, Bedi, Kurz, Banccroft, Miller [52]	2013	College Hockey	"An injury was defined as any event that directly resulted in an athlete being unable to participate in 1 or more games following the event."	Time Loss Definition	1.47/1000 AE (games .13/1000 AE (practice)	Contact with another player 77%	MCL	Total number of Injuries/Total AE x1000
Dalton, Zupon, Gardner, Djoka, Dompier, Kerr	2016	NCAA Ice Hockey	"A reportable injury occurred as a result of participation in an organized intercollegiate practice or competition and required the attention from an AT or a physician."	Medical Attention Definition	1.03/1000 AE	Non-contact 49.4%, overuse 17.6%	Strains 67.2%, Contusions 16.9%	Total Number of Injuries/numbe r of games x

[54]								average roster x1000
Longstaffe, Leiter, MacDonald [51]	2018	National Hockey League	Page 36 of 101N/A	N/A	Overall incidence rate: 0.42/1000 AE (TOI) 0.20/1000 AE (total games played)	Body contact 40.3%, incidental contact 25.4%	ACL	ACL injury per game hours: ACL injury/TOI (position specific) ACL per game exposure: ACL injury/total # of games played for every player

2.4 Discussion

Injury rates in men's elite ice hockey are higher in professional leagues such as the Swedish Elite League [31] and Finnish National League [33] than college hockey [19,20,23]. This may be due to the differing demands as professional players play more games in a season, and therefore may experience more overuse injuries. It may also be due to the athlete exposure estimation (player-game hours vs. player-games) used to calculate injury rate. Style of play and hockey rink dimensions are additional variables that may influence injury rate. Overall, we observed the trend that injury rates have increased over time in professional European leagues [35] and college hockey [39], while decreasing in men's international ice hockey[42].

We observed a wide range of injury definitions. This affects both the reliability and comparability of injury surveillance research. There is currently a consensus-based injury definition in sports such as soccer and rugby [10,11]; however, there is no consensus injury definition in ice hockey. We recommend that hockey forms a consensus injury definition as this will resolve an important issue that currently impedes hockey injury research. A consistent injury definition would create clarity as to which injury is considered a recordable event. We identified the International Ice Hockey Federation's (IIHF) definition of injury as the most appropriate as it only captures events that are sufficiently severe that they influence participation in practices or games. The IIHF's definition describes a reportable event as "any injury sustained in a practice or game that prevented the player from returning to the same practice or game; any injury sustained in a practice or game that caused the player to miss a subsequent practice or game; a laceration which required medical attention; all dental injuries; all concussions; all fractures" [42]. Although no single definition suits all needs, the time loss definition is the most common and easy to identify. It is considered reliable and allows for the comparison of data between teams, seasons and various leagues [45]. It is also used in other professional sports such as cricket and Australian football [57,58]. The choice of definition should reflect the aims and goals of surveillance. With its consistency, ease of use, and comparability of published data [8] among the most important variables, we feel the time-loss definition best meets the needs of injury surveillance in men's elite ice hockey. However, like all definitions there are limitations in choosing this metric. First, athletes often continue to compete in the presence of injury. Delaying treatment may lead to missed injuries. Finally, the threshold for time loss may depend on the time of season and how important the player is to team success [45]. Despite these drawbacks, we feel the strengths of the time-loss definition outweigh its limitations and that the IIHF's time-loss definition is warranted in elite men's ice hockey.

We also noted that athlete exposure estimations were inconsistent in the literature. The major confusion lies in how many participants are included in the injury rate calculation. Several researchers used player-game exposure based on the entire team, or average team roster (19 players) [20,36,37], while others used player-game hour exposures based on 6 players [18,21,24,30,34]. This leads to difficulty in interpreting injury rates and comparing research. It was proposed that the gold standard in athlete exposure during games is time on ice. As much as three times the amount of exposure was accounted for by estimating exposure rates using the player-game approximation compared to time on ice. However, when comparing the time on ice metric to the estimated player game-hour metric (based on one hour per game, rather than the actual amount of time that players spent on ice) it appears that this difference is small [4]. Therefore, the simplest and easiest way to calculate athlete exposure is to use six players on the ice (player-game hours) unless position specific injury rate information is warranted. Using a consistent athlete exposure metric will increase intra- and inter-league injury rate reliability.

Our review ~~i~~dentified that the knee is the most common site of lower body injury [20,22,33,39]. In particular, the MCL is the most commonly injured knee ligament in ice hockey [59]. In addition, hip related, soft tissue injuries of the groin may occur as a byproduct of body contact or overuse [24,54-56,60]. Soft tissue injuries to the groin may be due to the biomechanics of the hockey stride which involves eccentric contractions of the hip adductors [61].

The majority of studies reviewed found that collision with other players is the leading mechanism of injury as well as contact with the boards, opponent's hockey sticks and hockey pucks [22,35,36]. This leads to an injury paradox: the goal of the sports performance specialist is to build bigger, faster, stronger, leaner, more powerful, robust players. However, these types of players also travel faster, and hit harder, elevating the risk of injury. This situation emphasizes the need for accurate injury surveillance methods as these may help reinforce rules and/or govern the addition of new rules enforcing safety for active players, and specific testing that can be used to monitor fatigue, measure performance and guide rehabilitation should a lower-extremity injury occur.

2.4.1 Limitations

There are limitations to this study. There is a relative paucity of studies evaluating injury rates in men's elite ice hockey, and the definitions of injury and athlete exposures vary between studies. Accordingly, the reported injury rates differ between studies and are difficult to interpret. Two databases (PubMed and SPORTDiscus) were used to identify research papers that were relevant to injury definition, injury rates and athlete exposure in elite ice hockey. While these databases are an excellent source for research articles in sports, life sciences and biomedicine, supplemental databases may have identified additional research studies. Finally, we focused our review exclusively on males. Future research should focus on females as they have different types and rates of injury than males [62].

2.5 Conclusions

In summary, this project represents the first integrative literature review investigating injury rates, injury definition and AE in men's elite ice hockey. The greatest opportunities for continued improvement lie in both consistency and comparability to refine, improve and streamline calculations of injury rate.

At the current moment, a uniform definition of injury is the most important step to better objectify injury data in ice hockey. A universal definition is required by sport governing bodies and researchers. Though each approach has its limitations, in order to compare exposure rates in both the intra- and inter-league, a workable, consistent definition is required. Specific responsibility should be given in terms of who will diagnose the injury if the definition is a time loss definition, a medical attention definition, or a combination. In addition, a detailed injury list is needed to clarify the definition of injury and whether specific injuries such as dental, concussions, and facial lacerations, are included.

Finally, disparate AE estimations diminish injury rates, which compromises research findings. Attendance rate in both practice and games (player-game hours based on 6 players per game and the full roster during practices) is the preferred method for calculating athlete exposure.

2.5.1 Future Research

Investigating anatomical areas prone to injury is crucial for team performance staff such as athletic therapists, physical therapists and strength and conditioning specialists as it may guide rehabilitation initiatives, performance program design and athlete monitoring [63]. Player profiling in professional sports, such as soccer, is used to inform practice regarding readiness, return to play, and performance across sport coaches, exercise scientists and rehabilitation specialists [64]. We observed that lower extremity injuries are costly and common in the sport of ice hockey. Future research should be directed at specific testing tools that may be used to monitor fatigue [65], assess previous injury [66] and measure performance [67].

Future research should clearly define injury rate measurements to provide doctors, therapists, and coaches with accurate information to streamline return to play initiatives. In this regard, our review has exposed gaps including the disparate definition of injury and the lack of a consistent athlete exposure metric.

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Chapter 3

3 Reliability of the Single-Leg, Medial Countermovement Jump in Youth Ice Hockey Players

A version of this manuscript has been published in the journal Sports.

3.1 Introduction

Approximately one half of National Hockey League (NHL) players will experience an injury during the course of the season resulting in a loss of playing time. During the 2009–2010 and 2011–2012 seasons, researchers observed that injuries represented a total salary cost of $218 million per year for the NHL teams and their insurance companies [1]. The lower extremity was the most commonly injured area of the body, accounting for 30% of total annual lost salary [1]. The risk of injury is also a concern at the youth level, where lower extremity injuries account for approximately 20–40% of all injuries [2–4]. More than 50% of injuries in boys' ice hockey result in a minimum of one week of lost play [4]. Injury prevention programs must account for numerous physical qualities such as flexibility, power, strength and endurance in order to return players back to sport safely [5,6]. Functional performance tests have been used to assess physical qualities and determine rehabilitation timelines [7,8]. However, biomechanical and reliability considerations need to be examined prior to choosing each test.

Skating is an essential skill for ice hockey players. The authors will be referring to ice hockey when stating hockey for the remainder of the manuscript. The ice surface has a low coefficient of friction [9], precluding force along the skate blade [10]. Accordingly, propulsive force is created on the ice by pushing laterally with the foot [11]. On-ice propulsion involves frontal plane forces, which differs from sprinting on land. Sprinting on land involves force generation predominantly in the sagittal plane [12]. Propulsion occurs by pushing down and into the ground. Accordingly, the differences between the biomechanics of skating and sprinting indicate that these activities should have different performance tests.

Performance professionals use functional performance tests, such as the vertical jump, to assess performance and to guide the rehabilitation process [13,14]. However, the best tests for assessing readiness to return to sport are those that closely mimic the biomechanics of the sporting activity [5]. Vertical jumps and skating involve different push-off mechanics [15]. In both activities, the center of gravity is accelerated by the push-off force. However, push-off force in skating occurs by pushing laterally on the ice. Skaters rely on the reactive force that is perpendicular to the skate blade [16]. Skaters propel forward by external hip rotation, ankle and blade pronation and applying lateral force. These skating mechanics are not incorporated in the standard vertical jump. However, the single-leg, medial countermovement jump provides similar push-off mechanics as experienced in skating.

The reliability of kinetic and temporal variables in the single-leg, medial countermovement jump has been investigated and deemed reliable for field and court sport athletes [17], but not for hockey players. Establishing reliability of force and power variables in the single-leg, medial countermovement jump will support its use as a testing, training and rehabilitation tool used for youth hockey players. Accordingly, the primary purpose of this study was to determine the short-term reliability of the parameters involved in the single-leg, medial countermovement jump. We hypothesized that the single-leg, medial countermovement jump would be a reliable test in male youth hockey players.

3.2 Methods

3.2.1 Subjects and study design

A power analysis identified that ten participants provide 80% power to detect an intraclass correlation coefficient (ICC) of 0.7 at $p = 0.05$ [18]. Ten youth male ice hockey players from a 16U hockey team (16.10 ± 0.32 years old, 181.40 ± 5.38 cm, 78.76 ± 12.81 kg) playing in the Tier 1 AAA Elite Hockey League participated in this study. Participants represented all playing positions (forward, defense, goaltender). All participants had medical clearance from a healthcare professional to participate in this study and self-declared that they were free of any lower body musculoskeletal injuries. Inclusion criteria included no pre-existing medical conditions and currently participating in organized hockey. All participants received written explanation of the study and oral explanation of each test. The Western University Health Science Research Ethics Board approved the experimental protocol (protocol 113858).

3.2.2 Procedures

The participants were tested on two separate occasions, ten days apart. Testing took place indoors at the Donskov Strength and Conditioning training facility (Columbus, OH, USA), and at a hockey rink (Ice Haus, Columbus, OH, USA). Testing times, warm-ups and jump randomization were identical for both testing sessions. No familiarization trials were performed prior to collecting the single-leg, medial countermovement jumping trials; however, all participants were familiar with these jumps as they were part of their weekly in-season strength and conditioning sessions.

Participants completed a general warm-up consisting of 15 minutes of static stretching, mobility and dynamic movement (foam rolling, knee hugs, heel to butt, reverse lunge, single-leg deadlift with reach, “A” skips, back pedaling, short accelerations). All participants adhered to the standardized testing instructions. Participants performed three repetitions each, of both left and right single-leg, medial countermovement jumps. Jumps were performed in blocks for each direction, and the order of each block was randomized. Ground reaction forces during the jumps were measured using bilateral force plates (OR6-7, AMTI, Watertown, MA, USA). The force plate signals were sampled at 200 Hz with a 16-bit analog-to-digital converter (USB 6211, National Instruments, Austin, TX, USA) using a custom LabVIEW program (LabVIEW 2012, National Instruments, Austin, TX, USA). One minute of rest was provided between jumps to prevent fatigue [19].

3.2.3 Jump Protocol

All jump trials were administered by the same researcher using standardized verbal commands and demonstrations. Players were instructed to achieve the greatest vertical and horizontal displacement during each jump. Verbal encouragement was offered by the coaching staff to ensure maximal effort on each attempt. Compromised trials (improper technique, equipment malfunction) were discarded and repeated [20]. During the single-leg, medial countermovement jump, participants started standing with one foot on either force plate and then stood on the designated leg, squatted to a self-selected depth, and then jumped medially as far as possible to land on both legs on the ground. Arm swing was permitted. Two strength and conditioning professionals monitored all jumps to ensure proper jumping technique and safe landing mechanics.

3.2.4 Data Processing

All data analysis was performed using custom software in LabVIEW. We did not filter the force signals. The forces in the X, Y and Z directions were summed from each force plate to capture the forces applied through each limb, and to represent the total ground reaction force acting on the participant. The average of the three jump trials was used for analysis. Bodyweight was collected from standing trials. Jump phases were determined using an automated procedure, similar to previous research [21,22], and were verified using visual inspection. The initiation of the jump was defined as the point where lateral force increased 10 N above baseline. The end of the propulsive phase was defined as the point where the force dropped to less than 10 N. The start of the concentric phase for both vertical and lateral forces and accelerations was determined when the velocity of the center of mass became positive for more than 0.1 consecutive seconds (Figure 1). The net vertical impulse was calculated by subtracting the gravitational impulse from the total impulse. Vertical and lateral take off velocities were calculated using the impulse momentum relationship. Vertical and lateral power were calculated as the product of velocity and force. Maximum force was extracted from the force-time curves. Peak concentric power, average concentric power and average concentric power in the last 100 ms were extracted from the power curves.

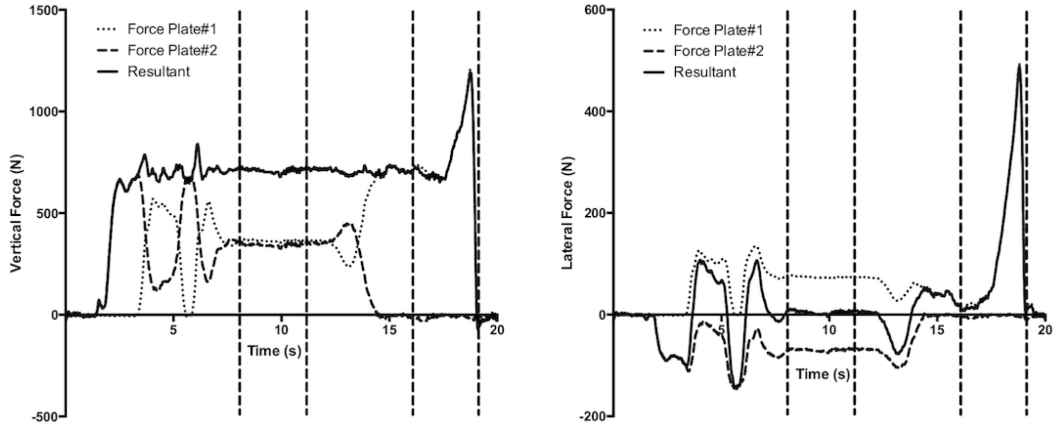

Figure 3.1 Vertical (left panel) and lateral (right panel) forces during a single-leg, medial countermovement jump from a representative trial. The three traces represent force plate #1 (dotted line), force plate #2 (dashed line) and resultant force (solid line). From left to right on each panel, the four vertical dashed lines reflect the beginning and end of standing prior to the jump, the initiation of jump (lateral forces >10 N) and end of jump.

Force was expressed in N (i.e., not normalized to body weight) and power was expressed in W (i.e., not normalized). Force was also expressed relative to body weight, for both lateral and vertical maximal forces.

3.2.5 Statistical Analysis

A Pearson correlation matrix was created in order to identify the relationships among variables in the single-leg, medial countermovement jump. This was based on the average of the three jump performances from both test sessions. The size of the correlation was evaluated as follows: $r < 0.7$ low; $0.7 \leq r < 0.9$ moderate, and $r \geq 0.9$ high [23]. Coefficients of determination (r^2) were calculated to indicate the percent of common variance explained by the correlation [24]. Shapiro–Wilk tests were used to assess data normality [25]. Normal data are presented as mean ± one standard deviation (SD).

Reliability analyses were performed using the Hopkins spreadsheet [26]. A variety of reliability calculations were used as there is no gold standard for this test [27,28]. A two-way random-effects model ICC (3,1) was used to evaluate relative reliability [27]. Values less than 0.5, between 0.5 and 0.75, between 0.75 and 0.9, and greater than 0.9 were interpreted as poor, moderate, good, and excellent reliability, respectively [29]. The standard error of measurement (SEM) was used to assess absolute reliability [30]. Relative SEM (SEM%) was quantified by dividing the SEM by the mean of all the data from the two test occasions. The smallest real difference (SRD) was calculated by multiplying the SEM by 1.96 and by the square root of 2.0 to include 95% of the observations of the difference between the two measurements [30]. The normalized SRD, expressed as a percentage (SRD%), was calculated by dividing the raw SRD by the mean of all the data from the two test occasions.

3.3 Results

Normality was confirmed ($p > 0.05$) for all variables. The strength of the relationships between variables are presented in the correlation matrix (Table 1). There was a high correlation between vertical concentric average power in the last 100 ms and vertical peak concentric power ($r = 0.99$). In addition, a near-perfect relationship was observed for lateral concentric average power in the last 100 ms and lateral peak concentric power ($r = 0.99$). Several notable relationships were observed among the variables including a moderate relationship between maximum vertical force and peak lateral concentric power ($r = 0.72$), an inverse relationship between vertical takeoff velocity and lateral takeoff velocity ($r = -0.36$), and a large degree of independence between average and peak concentric power for both the lateral and vertical directions ($r = 0.58$; $r^2 = 0.33$ and $r = 0.63$; $r^2 = 0.40$, respectively).

The reliability of the variables of interest are presented in Table 2. We observed moderate-to-excellent reliability for all twelve variables of interest (ICCs between 0.50 and 0.98) for both right and left jumps. Excellent reliability for both right and left leg jumps was observed for maximum lateral force, maximum vertical force, and vertical average concentric power in the last 100 ms (ICCs > 0.91). The SRD%s ranged from 5.2 to 6.5% for maximum vertical force for both left and right legs, to 14.8 to 16.5% for vertical average concentric power during the last 100 ms for both the left and right legs. The SEM%s also ranged for each variable with maximum vertical force at 1.9% and 2.3% for the left and right legs to 5.35% and 5.9% for vertical average concentric power during the last 100 ms for both the left and right legs.

Table 3.1 Pearson Correlation Matrix for the parameters derived from the single-leg, medial countermovement jump.

Parameter	VERT VTO (m/s)	VERT Jump Height (cm)	VERT Peak Concentric Power (W)	VERT Average Concentric Power (W)	VERT Average Concentric Power 100 ms (W)	LAT VTO (m/s)	LAT Peak Concentric Power (W)	LAT Average Concentric Power (W)	LAT Average Concentric Power 100 ms (W)	Maximum VERT Force (N)	Max VERT Force above Body Weight (%BW)	Maximum LAT Force (N)
VERT jump height (cm)	1.00											
VERT peak con power (W)	0.77	0.77										
VERT Avg con power (W)	0.55	0.55	0.58									
VERT Avg con Power 100 ms (W)	0.76	0.76	1.00	0.58								
LAT VTO (m/s)	−0.36	−0.36	−0.08	−0.09	−0.05							
LAT peak con power (W)	−0.18	−0.18	0.32	0.13	0.34	0.84						
LAT Avg con power (W)	−0.30	−0.30	0.02	0.48	0.03	0.61	0.63					
LAT Avg con power 100 ms (W)	−0.20	−0.20	0.32	0.10	0.34	0.85	1.00	0.63				
Max VERT force (N)	0.22	0.220	0.77	0.42	0.77	0.30	0.72	0.45	0.72			
Max VERT force above body weight (%BW)	0.40	0.40	0.52	0.27	0.50	−0.09	0.13	0.17	0.15	0.55		
Max lateral force (N)	−0.07	−0.07	0.50	0.19	0.51	0.63	0.95	0.54	0.94	0.86	0.26	
Max LAT force above body weight (%BW)	−0.22	−0.22	0.07	−0.14	0.08	0.70	0.78	0.43	0.77	0.41	0.29	0.73

VERT: vertical; VTO: vertical takeoff velocity; LAT: lateral; LVTO: lateral takeoff velocity; Max: maximum; Con: concentric; %BW: percent bodyweight. Correlation coefficient magnitudes larger than 0.3125 are statistically significant at $p < 0.05$.

Table 3.2 Test–retest reliability for the parameters involved in the single-leg, medial countermovement jump.

Single-Leg, Medial Countermovement Jump Force and Velocity Variables						
Lateral Force/Velocity	Mean (SD) Trial 1	Mean (SD) Trial 2	SEM	Typical Error (90% CI)	SRD	ICC (90% CI)
(R) Max LAT Force (N)	487.0 (87.0)	510.2 (85.4)	11.0	12.8 (9.4–21.2)	30.6	0.98 (0.95–0.99)
(L) Max LAT Force (N)	504.1 (79.0)	502.2 (83.5)	23.6	27.8 (20.8–45.8)	65.4	0.91 (0.74–0.97)
(R) Max LAT force above body weight (%BW)	65.1 (4.9)	68.0 (4.8)	1.9	2.1 (1.5–3.5)	5.2	0.85 (0.59–0.950
(L) Max LAT force above body weight (%BW)	67.6 (5.4)	67.0 (5.8)	3.5	3.8 (2.8–6.3)	9.6	0.59 (0.10–0.85)
(R) LAT VTO (m/s)	2.24 (0.18)	2.18 (0.15)	0.05	0.05 (0.04–0.09)	0.15	0.91 (0.76–0.97)
(L) LAT VTO (m/s)	2.22 (0.22)	2.20 (0.18)	0.11	0.11 (0.08–0.18)	0.31	0.75 (0.38–0.91)
Vertical Force/Velocity						
(R) Max VERT Force (N)	1272 (181.2)	1273 (190.8)	29.6	35.6 (26.0–58.6)	82.1	0.97 (0.92–0.99)
(L) Max VERT Force (N)	1304 (200.7)	1261 (188.6)	24.4	27.9 (20.4–46.0)	67.9	0.98 (0.95–1.00)
(R) Max VERT force above body weight (%BW)	70.8 (11.4)	70.1 (10.9)	4.6	4.9 (3.6–8.2)	12.6	0.84 (0.57–0.95)
(L) Max VERT force above body weight (%BW)	74.8 (11.7)	68.3 (9.4)	3.5	3.6 (2.6–6.0)	9.7	0.91 (0.74–0.97)
(R) VERT VTO (m/s)	1.38 (0.16)	1.35 (0.08)	0.12	0.09 (0.07–0.16)	0.32	0.50 (−0.03–0.81)
(L) VERT VTO (m/s)	1.37 (0.27)	1.30 (0.27)	0.10	0.11 (0.08–0.19)	0.29	0.85 (0.59–0.95)
Single-Leg, Medial Countermovement Jump Power Variables						
Lateral Power	Mean (SD) Trial1	Mean (SD) Trial2	SEM	Typical Error (90% CI)	SRD	ICC (90% CI)
(R) LAT peak con power (W)	925.1 (225.2)	945.3 (209.2)	38.6	43.6 (31.8–71.7)	107.1	0.97 (0.91–0.99)
(L) LAT peak con power (W)	934.9 (204.1)	930.8 (206.7)	84.8	95.9 (67.0–157.8)	235.1	0.82 (0.54–0.94)
(R) LAT Avg con power (W)	406.6 (135.8)	370.4 (117.5)	53.9	56.6 (41.3–93.2)	149.4	0.84 (0.57–0.95)
(L) LAT Avg con power (W)	377.3 (164.7)	378.6 (150.9)	90.5	94.2 (68.7–155.0)	250.8	0.70 (0.28–0.89)
(R) LAT Avg con power (100 ms; W)	873.1 (221.8)	887.7 (207.0)	28.0	31.9 (23.2–52.4)	77.7	0.98 (0.95–0.99)
(L) LAT Avg con power (100 ms; W)	886.9 (199.2)	879.9 (193.1)	73.8	82.0 (59.8–134.9)	204.6	0.86 (0.62–0.95)
Vertical Power						
(R) VERT peak con power (W)	1663.5 (306.7)	1668 (254.8)	104.6	109.2 (79.7–179.8)	290.2	0.88 (0.67–0.96)
(L) VERT peak con power (W)	1690.4 (458.5)	1591 (382.9)	127.2	134.7 (98.3–221.7)	352.7	0.92 (0.77–0.98)
(R) VERT Avg con power (W)	710.6 (225.3)	686.1 (199.2)	84.6	90.1 (65.7–148.3)	234.7	0.85 (0.61–0.95)
(L) VERT Avg con power (W)	607.0 (131.8)	638.3 (189.2)	70.0	94.4 (68.9–155.4)	194.2	0.72 (0.31–0.90)
(R) VERT Avg con power 100 ms (W)	1582.1 (310.1)	1616 (256.2)	95.2	99.8 (72.8–164.3)	263.9	0.91 (0.73–0.97)
(L) VERT Avg con power 100 ms (W)	1621.0 (445.0)	1556 (368.1)	128.4	135.2 (98.6–222.4)	356.0	0.92 (0.76–0.97)

R: right leg; L: left leg; VERT: vertical; LAT: lateral; Avg: average; con: concentric; SD: standard deviation; SEM: standard error of measure; SRD: smallest real difference; CI: confidence interval; LAT VTO: lateral takeoff velocity; VERT VTO: vertical takeoff velocity; %BW: percent bodyweight; ICC: intraclass coefficient.

We observed good reliability for lateral takeoff velocity, maximal vertical force above body weight (%BW), lateral peak concentric power, lateral average concentric power during the last 100 ms, and vertical peak concentric power for both right and left jumps (ICCs between 0.75 and 0.98). The SRD%s ranged from 6.7% to 14% for lateral takeoff velocity for both the right and left legs, to 17.4% and 21% for vertical peak concentric power for both the right and left legs. The SEM%s ranged from 2.2 to 4.9% for lateral takeoff velocity on the right and left legs to 6.2 to 7.7% for peak concentric power on the right and left legs, respectively.

Moderate reliability was observed for maximum lateral force above body weight (%BW), vertical takeoff velocity, lateral average concentric power and vertical average concentric power in both legs. Minimal differences were found between trial one and two for vertical average concentric power (710.66 ± 225.30 W vs. 686.18 ± 199.27 W right leg, 607.04 ± 131.84 vs. 638.30 ± 189.26 W left leg). Inter-limb reliability differences were observed for each parameter; however, all parameters met the moderate-to-excellent rating. The right limb sustained higher reliability in all lateral force, velocity and power parameters, while the left limb sustained higher reliability during all vertical force, velocity and power parameters with the exception of vertical average concentric power.

3.4 Discussion

The primary purpose of this study was to determine the short-term reliability of the parameters involved in the single-leg, medial countermovement jump. We hypothesized that the single-leg, medial countermovement jump would be a reliable test in male youth hockey players. Our hypothesis was supported for all twelve discrete variables.

Research in field-based sports has concluded that the medial countermovement jump can be used to reliably measure force and power in the frontal plane [17,31]. The current research extends this finding by demonstrating that it is reliable in measuring force and power in youth hockey players. Given biomechanical similarities between this jump and the propulsion phase in skating, it is likely that this jump is an important off-ice test to evaluate skating performance. To our knowledge, this paper is the first to present SEMs and relative SEMs for the various jump variables associated with the single-leg, medial countermovement jump. These numbers serve as baseline measures for future research.

Other metrics have been used to assess skating performance including the vertical jump, squat jump, forty-yard dash, thirty-meter test, broad jump, and the triple hop jump test [32–34]. Studies vary in concluding which test most accurately assesses on-ice skating performance. One study observed that vertical jump impulse, as measured on force plates, was one of several variables that best assessed on-ice skating performance [32], while others have stated that the thirty-meter sprint and triple hop were superior [33]. Finally, in determining the measurement device and jumping protocol most appropriate for testing elite hockey players, one study concluded that the Vertec squat jump was superior to the Just Jump mat for measuring lower body power [35]. True countermovement is uncommon in ice hockey as players rarely use the stretch-shortening cycle to enhance muscle contraction [31]. In addition, push-off on the ice is different than on land. Hockey players must push off laterally in order to create propulsive force. This push-off is similar to the single-leg, medial countermovement jump. Since the best tests for assessing readiness to return to sport are those that closely mimic the biomechanics of the sporting activity [5], the single-leg, medial countermovement jump appears to be an excellent functional performance test for skating.

Other studies have measured the reliability of the single-leg, medial countermovement jump. Measuring distance jumped showed a pooled ICC of 0.97 for both men and women with intrasubject variability, expressed as a coefficient of variation, of 4.6% [36]. However, the use of measures such as distance jumped does not measure ground reaction forces. Individuals recovering from lower-extremity injuries employ unique jumping strategies that may not present when measuring distance jumped. While injured, an athlete may select a movement strategy that avoids force application to the injured limb [37]. Therefore, the use of force plates to measure ground reaction forces and leg asymmetries is critical for both healthy and injured athletes [37]. Vertical and lateral ground reaction forces during the single-leg, medial countermovement jump were investigated for field and court sport athletes [17]. For the concentric variables, peak vertical force (ICC = 0.96), peak lateral ground reaction (ICC = 0.89) and peak vertical power (ICC= 0.86) were reliable measures. Similarly, our investigation observed ICCs ranging from 0.88 to 0.98 for these variables. The single-leg, medial countermovement jump has also differentiated between elite and non-elite soccer players [31]. Researchers observed that single-leg jumps such as the unilateral vertical jump, unilateral horizontal jump and unilateral medial countermovement jump could differentiate elite from non-elite soccer players and therefore should be included in power profiling assessments.

Lateral push-off, during which forces are produced perpendicular to the skate blade, occurs in a short window of time [15]. Our results suggest that this can be measured using the medial countermovement jump. Mean average lateral concentric power during the last 100 ms prior to push-off showed good-to-excellent reliability (ICC = 0.86–0.98). In addition, the single-leg, medial countermovement jump displayed larger horizontal takeoff velocities than vertical takeoff velocities. Vertical takeoff velocity was 61% of total lateral takeoff velocity during right and left leg propulsion. This suggests that larger horizontal forces were needed to move the center of mass effectively during this jump, solidifying its use for measuring hockey player performance.

From an injury-risk perspective, the single-leg, medial countermovement jump may be useful for measuring force, velocity and power of the lower limbs prior to potential injury occurrence. This provides objective information to the performance staff and may serve to guide rehabilitation during return to play. In addition, the single-leg, medial countermovement jump may be used to assess and track asymmetries between right and left limbs in both healthy and injured athletes. It has been noted that interlimb differences of greater than ten percent lead to a fourfold increase in re-rupture of the ACL in athletes [38]. Having a reliable, frontal plane test that can provide information pertaining to jump performance may be used to improve return-to-play procedures in hockey.

A number of features of the single-leg, medial countermovement jump are similar to skating. For example, it has a high concentric effort, minimal stretch-shortening cycle, arm swing to assist propulsion, and frontal plane force production. These features of the single-leg, medial countermovement jump substantiate its face validity as an assessment of skating propulsion. Accordingly, it may be an important test for ice hockey players.

3.4.1 Limitations

There are limitations to this study. This study tested a narrow age range of male youth athletes playing in a single youth hockey league. Future research should evaluate this jump with a broader age range of hockey players. In addition, female players have different skating biomechanics [10]. Accordingly, future research should be performed on female players. We included players of different playing positions, which may have affected results. Further research should evaluate whether there are systemic differences in single-leg, medial countermovement jump performance between player positions. We did not ask our participants about limb dominance, and therefore are unable to evaluate whether the bilateral differences in reliability may be due to limb dominance. Lastly, the location of testing may have affected performance. Testing took place both at the gym and at the rink. Different locations and temperatures may have altered physiologic behavior, causing a potential change in performance.

3.5 Conclusions

All twelve discrete variables examined showed moderate-to-excellent between-session reliability. Specifically, both lateral and vertical ground reaction forces showed the highest reliability. Lateral takeoff velocity and lateral average concentric power during the last 100 ms showed good reliability. As a result, performance professionals can feel confident using these variables extracted from single-leg, medial countermovement jumps to gauge hockey player performance.

In conclusion, the results from this study suggest that the single-leg, medial countermovement jump is a reliable test of frontal plane force production for youth hockey players. The fact that the single-leg, medial countermovement jump allows the tester to measure single-leg ground reaction forces and power in the frontal plane makes this test a relevant option in all phases of sport performance and rehabilitation. A larger sample size including athletes of different ages is needed to evaluate changes with training and recovery from injury for ice hockey players.

3.6 References

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Chapter 4

4 Normative Reference of the Single Leg, Medial Countermovement Jump in Adolescent Youth Ice Hockey Players

A version of this manuscript is currently under revision in the journal Sports.

4.1 Introduction

Ice hockey has become one of the most popular sports played in North America with 561,700 players under 18 years of age registered with USA Hockey in 2019-2020 [1]. As players mature, a greater emphasis is placed on their skill and physical development, resulting in improved upper body strength and lower body power [2]. Consequently, physical preparation training and testing is paramount for tracking progress and improvement over time [3]. Tests, such as the countermovement jump, squat jump, and three hop jump have been employed to measure physical performance [4,5]. However, the best tests for assessing physical capacities and return to sport are those that closely mimic the biomechanics of the sporting activity [6]. The single leg, medial countermovement jump is a reliable measure of assessing youth hockey player performance [7]. Nevertheless, normative values across multiple youth ice hockey age groups have yet to be reported.

The single leg, medial countermovement jump is a lower body power test that incorporates a high degree of force, velocity and coordination in the frontal plane. It has been used to assess the unilateral power output of field and court sport athletes [8,9]. One study has examined the reliability of various temporal and kinetic variables involved in jumping vertically, horizontally and medially [8]. This study determined that eccentric and concentric peak force and concentric peak power were the only reliable measures between single leg vertical, horizontal and medial jumps [8]. Another group of researchers determined that single leg, countermovement jumping could differentiate between elite and non-elite soccer players [10]. Researchers reported that elite soccer players produced more peak vertical power than non-elite players during single leg jumps in the vertical, horizontal and medial directions, but these differences were not significant for bilateral jumps. They concluded that single leg jumping was more useful than the traditional bilateral countermovement jumping [10]. Single leg jumping is also appropriate for evaluating skating as it involves lateral propulsion on one leg. Velocity, force and power parameters describing performance of the single leg, medial countermovement jump demonstrate moderate to strong test re-test reliability in a group of U16 youth ice hockey players [7]. Accordingly, it is important to further explore the measurement properties and baseline normative values for the single leg, medial countermovement jump.

Interlimb asymmetry has also been explored for a variety of styles of single leg jumps in the vertical and horizontal directions [11,12]. Researchers determined that the single leg, vertical countermovement jump showed greater side-to-side differences compared with single, triple and crossover hops for distance, illustrating that single leg jumps may be particularly suited for assessing asymmetry. Asymmetry has important implications for performance as the degree of asymmetry in the single leg, countermovement jump was correlated with sprint times across distances of 5, 10 and 20 m in youth female soccer players [11]. Interlimb asymmetries are also inversely correlated with jumping ability [13]. Inter-limb differences have not been reported in elite youth ice hockey players. Assessing differences in strength, power and performance between legs is important for skill and physical development as well as injury prevention and rehabilitation [14].

To the best of our knowledge, normative force and power values, as well as interlimb asymmetries of the single leg, medial countermovement jump have not been reported for ice hockey players of multiple age groups. These normative measures would be valuable for performance professionals to compare their athletes to normative baselines. Furthermore, normative data about interlimb asymmetries may be useful for performance staff to monitor rehabilitation progress and return to play timelines. Therefore, the purposes of this study were to measure normative single leg, medial countermovement jump parameters (i.e., maximum force, average concentric power and average concentric power during the last 100 ms) amongst youth ice hockey players, and to assess the interlimb asymmetry between legs in these healthy athletes.

4.2 Materials and Methods

4.2.1 Subjects and Study Design

In this study, 91 elite performing youth ice hockey players from 10U, 11U, 12U, 13U, 14U, 15U, 16U and 18U teams participated. Group characteristics are provided in Table 1. All participants had medical clearance from a healthcare professional. Inclusion criteria for all subjects included no pre-existing medical conditions, no current lower body musculoskeletal injuries, and currently participating in organized hockey. Testing for the 14U-18U age groups took place during the last month of the 2019-2020 hockey season, when training volume was low in preparation for league playoffs. Testing for the 10U-13U age groups took place at training camp in August prior to the start of the 2020-2021 hockey season. Prior to participation, all subjects gave written informed consent to participate in the study. The University of Western Ontario Health Science Research Ethics Board approved the experimental protocol (protocol 113858).

Table 4.1 **Demographics (mean ± SD) for the youth ice hockey age groups.**

Group	Number*	Age (years)	Height (cm)	Mass (kg)
10U	15	9.8 ± 0.4	141.8 ± 6.2	34.9 ± 6.2
11U	6	11.0 ± 0.0	148.6 ± 5.7	40.6 ± 5.7
12U	11	11.8 ± 0.4	152.4 ± 3.9	43.2 ± 6.6
13U	14	12.9 ± 0.3	164.0 ± 9.8	51.7 ± 10.0
14U	8	14.0 ± 0.5	173.0 ± 3.9	68.6 ± 9.1
15U	18	15.2 ± 0.4	176.3 ± 6.7	72.3 ± 8.6
16U	10	15.9 ± 0.4	179.9 ± 6.5	77.1 ± 12.0
18U	9	17.6 ± 0.7	180.9 ± 7.1	75.2 ± 7.1

*Number of participants in each ice hockey age group.

4.2.2 Procedures

Testing for the 14U-18U players took place indoors at Donskov Strength and Conditioning (Columbus, Ohio, USA) training facility. Testing for the 10U-13U players took place at the Ice Haus hockey rink (Columbus, Ohio, USA). A familiarization period was not provided prior to testing for the 14U-18U players; however, all participants were familiar with these jumps as they were part of their weekly in-season strength and conditioning plan. The 10U-

13U players were familiarized with these jumps by their skill coaches as part of their weekly dynamic warm-ups. Each participant completed their testing in one session.

Participants performed a standardized 15-minute warmup consisting of static stretching, mobility and dynamic movement (foam rolling, knee hugs, heel to butt, reverse lunge, single leg deadlift with reach, A skips, back pedaling, short accelerations). Participants performed single leg, medial countermovement jumps on both left and right legs for three repetitions each. Jumps were performed in randomized ordered blocks for each leg. Jump ground reaction forces were measured using bilateral force plates (OR6-7, AMTI, Watertown, MA, USA). A custom LabVIEW program (LabVIEW 2012, National Instruments, Austin TX) sampled the force plate signals at 200 Hz with a 16-bit analog-to-digital converter (USB 6211, National Instruments, Austin TX). One-minute of rest was provided between each jump to prevent fatigue [15].

4.2.3 Jump Protocol

Standardized verbal commands and demonstrations were administered to all participants by the same staff member. Maximal effort on each jump attempt was encouraged by verbal support from the coaching staff. During the single leg, medial countermovement jump, participants squatted to a self-selected depth on the designated leg, while standing on a force plate, and then jumped medially as high and as far as possible landing on both legs. Arm swing was permitted. All jumps were monitored by two strength and conditioning professionals to ensure proper jumping technique. Compromised trials (improper technique, equipment malfunction) were discarded and repeated.

4.2.4 Data processing

Force plate data was analyzed using custom software in LabVIEW. The forces in the X, Y and Z directions were summed from each force plate. Participants' bodyweight was collected from standing trials. Jump phases were automatically determined and verified via visual inspection. Jump initiation was defined as the point of time where lateral force started to increase. The point where the vertical force dropped to less than 10 N was defined as the end of the jump/task. The initiation of the concentric phase for both vertical and lateral forces and accelerations was determined when velocity of the center of mass became positive for longer than 0.1 consecutive seconds. The product of velocity and force was used to calculate vertical and lateral power. Maximum force was extracted from the force-time curve. Average concentric power and average concentric power in the last 100 ms were extracted from the power curve. Force and power were expressed in raw units (N and W). In summary, the variables included vertical and lateral maximal force, average concentric power, and average concentric power during the last 100 ms. These variables are a subset of the parameters that were determined to be reliable in a recent study [7]. This subset was selected as these parameters assess independent constructs (based on low correlations). Jump performances were represented as the average of the parameters from the three jump trials.

4.2.5 Statistical Analysis

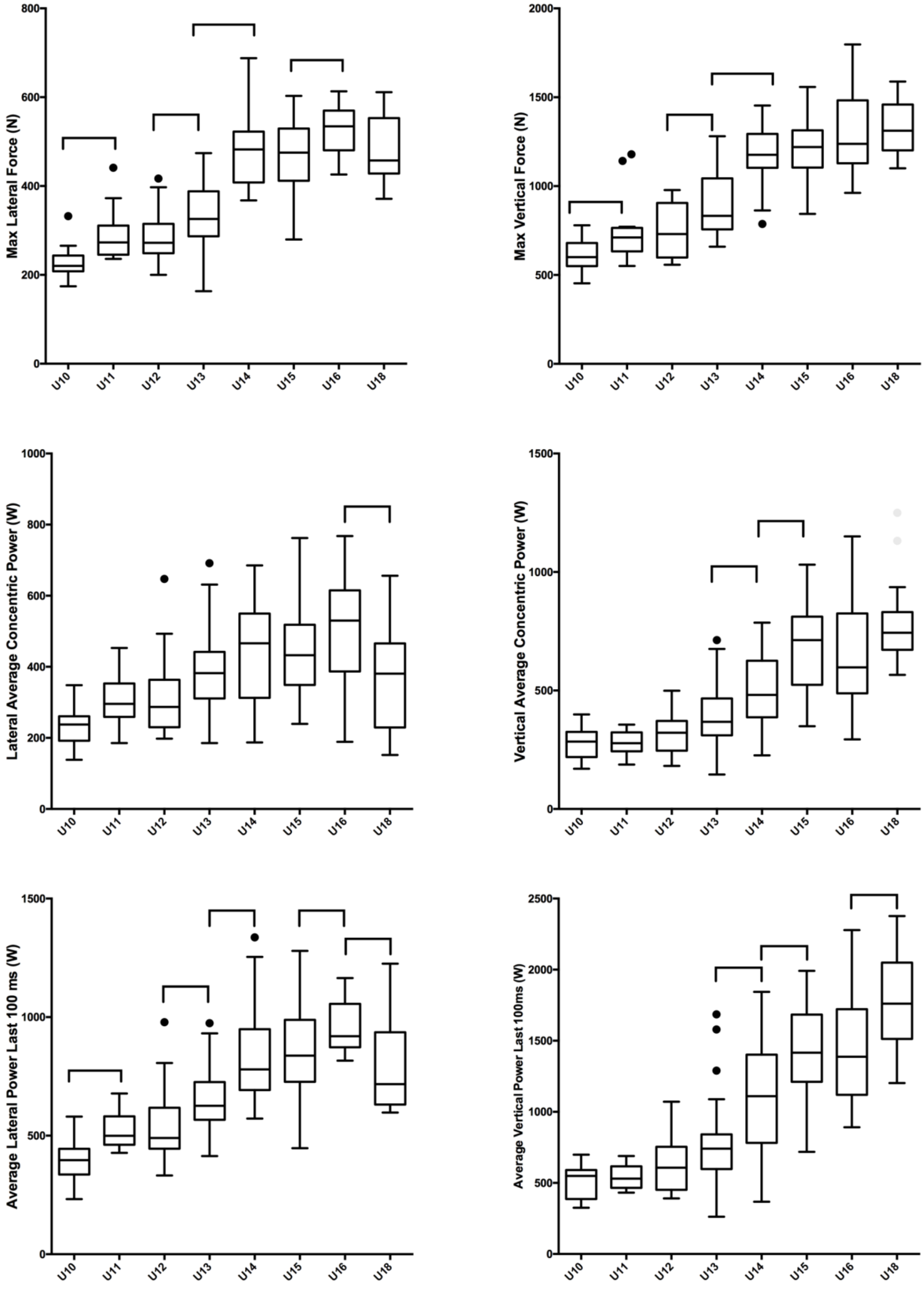
To account for outliers and uneven distributions within groups, non-parametric analyses were used [16]. Mann-Whitney U tests compared left and right leg jump performance for all six variables within each of the eight age groups. The false discovery rate method was used to control familywise error rate for all Mann-Whitney U tests, with a 0.05% threshold [17]. Data for the right and left sides will be amalgamated if the differences between sides are not statistically significant. Kruskal-Wallis tests will be used for between-group comparisons between age groups. Finally, Mann-Whitney U post hoc tests will identify significantly different age pairs for each of the six jump parameters; only adjacent age groups (e.g., U10 vs U11, U11 vs U12) will be compared and the false discovery rate method will be used to control familywise error rate. Effect sizes and 95% confidence intervals will be calculated for all adjacent age groups using the probability of superiority approach [18], and interpreted as values of 0.56, 0.64 and 0.71 corresponding to small, medium and large effect sizes [19]. Jump parameter characteristics will be presented as box and whisker plots including the median, with boxes illustrating the first (Q1) and third quartiles (Q3), and whiskers are extended 1.5 times the length of the interquartile range beyond the box boundaries, defining the inner fence for identifying outliers [20].

Interlimb asymmetry index calculations were recorded for each participant and averaged for each team using the percentage difference between limbs calculation [21,22]. Statistical analysis will be performed using Prism (V9.1.0, GraphPad Software LLC., San Diego, CA).

4.3 Results

There were no statistically significant differences between the force and power parameters for the right and left leg jump performances for any of the age groups after false discovery rate adjustment. Consequently, all normative values are based on the combined right and left scores for each participant.

In general, all of the power and force parameters for the single leg, medial countermovement jumps increased with age (Figures 1). The details of the statistical analysis and the effect sizes are reported in Table 2. Most parameters were significantly different between the ages of 13 and 14; the 14U group outperformed the 13U group by 23-30% in five of the six jumps. As a general trend, both younger (10U-12U) and older (15U-18U) age groups experienced fewer differences between age groups. The 11U group had significantly larger scores than the 10U group in three of the six performance parameters, while there were no significant differences observed between the 11U and 12U age groups. In addition, two significant differences were observed between the 14U and 15U age groups for vertical parameters, and between the 15U and 16U age groups for lateral parameters. Finally, the lateral jump parameters for the 16U age group were larger by 8-34% compared to the 18U group; however, only two were statistically significant (p-values ranging from 0.002 - 0.010). The vertical parameters for the 18U age group were 3-20% larger than the 16U age group; however, only vertical average concentric power during the last 100 ms was statistically significant (p = 0.006).


Max Lateral Force (N)
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Max Vertical Force (N)
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Average Vertical Power Last 100ms (W)
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Figure 4.1 Box and whisker plots comparing youth ice hockey single leg, countermovement jump variables across each age group. Panels A and B illustrate the maximum lateral and vertical force, respectively. Panels C and D illustrate the lateral and vertical average concentric power, respectively. Panels E and F illustrate the average lateral and vertical power in the last 100 ms, respectively. Whiskers are extended 1.5 times the length of the interquartile range beyond the box boundaries, defining the inner fence for identifying outliers. Data points that are outside of these fences are identified with individual points. Significant differences ($p < 0.05$) between adjacent age groups are indicated with brackets. Note that the scales are different for the lateral and vertical panels.

Table 4.2 Median difference, statistical significance and effect sizes of adjacent age group comparisons.

Parameter	Hodges-Lehmann Median Difference	m	n	U	False Discovery Rate Threshold	P-Value*	Effect Size (95% CI)
				VERT Avg Con Power (W)			
10U vs 11U	-3.95	19	12	111	0.050	0.921	0.513 (0.318 - 0.703)
11U vs 12U	36.73	12	21	99	0.036	0.326	0.607► (0.403 - 0.775)
12U vs 13U	68.59	21	28	193	0.027	0.042	0.672►► (0.507 - 0.799)
13U vs 14U	109.80	28	16	123	0.014	0.013❖	0.725►►► (0.547 - 0.847)
14 U vs 15U	174.50	16	36	144	0.007	0.003❖	0.750►►► (0.581 - 0.861)
15U vs 16U	-27.00	36	20	338	0.043	0.716	0.530 (0.377 - 0.677)
16U vs 18U	132.50	20	18	109	0.021	0.038	0.697►► (0.511- 0.830)
				VERT Avg Con Power 100 ms (W)			
11U vs 12U	16.58	19	12	101	0.043	0.617	0.557 (0.356 - 0.738)
11U vs 12U	64.43	12	21	99	0.036	0.326	0.607► (0.403 - 0.775)
12U vs 13U	129.10	21	28	196	0.027	0.048	0.667►► (0.501 - 0.794)
13U vs 14U	343.70	28	16	110	0.007	0.004❖	0.754►►► (0.578 - 0.868)
14U vs 15U	321.20	16	36	153	0.021	0.007❖	0.734►►► (0.564 - 0.850)
15U vs 16U	-13.90	36	20	354	0.050	0.925	0.508 (0.357- 0.657)
16U vs 18U	385.90	20	18	87	0.014	0.005❖	0.758►►► (0.574 - 0.874)
				LAT Avg Con Power (W)			
10U vs 11U	65.38	19	12	49	0.007	0.007	0.785 (0.576 - 0.902)
11U vs 12U	-12.05	12	21	118	0.043	0.782	0.532 (0.337 - 0.716)
12U vs 13U	77.96	21	28	184	0.021	0.024❖	0.687►► (0.522 - 0.811)
13U vs 14U	67.93	28	16	164	0.036	0.148	0.634► (0.455 - 0.778)
14U vs 15U	1.19	16	36	286	0.050	0.977	0.503 (0.342 - 0.664)
15U vs 16U	63.26	36	20	260	0.029	0.089	0.638► (0.479 - 0.768)
16U vs 18U	-138.90	20	18	93	0.014	0.010❖	0.741►►► (0.557 - 0.862)
				LAT Avg Con Power 100 ms (W)			
10U vs 11U	121.90	19	12	24	0.007	0.001	0.894 (0.705 - 0.965)
11U vs 12U	-4.11	12	21	121	0.050	0.868	0.519 (0.327 - 0.706)
12U vs 13U	123.70	21	28	154	0.029	0.004❖	0.738►►► (0.575 - 0.849)
13U vs 14U	171.00	28	16	80	0.014	<0.001❖	0.821►►► (0.652 - 0.914)
14U vs 15U	40.51	16	36	248	0.043	0.437	0.569► (0.402 - 0.720)
15U vs 16U	97.24	36	20	208	0.036	0.008❖	0.711►►► (0.553 - 0.826)
16 U vs 18U	-203.40	20	18	79	0.021	0.002❖	0.780►►► (0.599 - 0.889)
				MAX VERT Force (N)			
10U vs 11U	105.70	19	12	56	0.021	0.018❖	0.754►►► (0.543 - 0.882)
11U vs 12U	18.63	12	21	113	0.050	0.645	0.552 (0.354 - 0.732)

12U vs 13U	148.80	21	28	160	0.014	0.006❖	0.728►►►(0.565 - 0.842)
13U vs 14U	289.50	28	16	62	0.007	<0.001❖	0.862►►►(0.700 - 0.939)
14U vs 15U	46.74	16	36	249	0.043	0.449	0.568►(0.400 - 0.719)
15U vs 16U	42.09	36	20	314	0.036	0.439	0.564►(0.408 - 0.706)
16U vs 18U	63.59	20	18	150	0.029	0.393	0.583►(0.401 - 0.742)
MAX LAT Force (N)							
10U vs 11U	49.61	19	12	24	0.007	<0.001❖	0.895►►►(0.705 - 0.965)
11U vs 12U	1.14	12	21	123	0.050	0.926	0.512 (0.321 - 0.699)
12 U vs 13U	51.77	21	28	159	0.021	0.005❖	0.729►►►(0.566 - 0.843)
13U vs 14U	136.00	28	16	34	0.014	<0.001❖	0.924►►►(0.781 - 0.974)
14U vs 15U	-7.38	16	36	271	0.043	0.746	0.529 (0.365- 0.686)
15U vs 16U	56.71	36	20	205	0.029	0.007❖	0.715►►►(0.557 - 0.829)
16U vs 18U	-46.47	20	18	113	0.036	0.051	0.686►►(0.499 - 0.822)

m, n and U refer to the number of participants in the two groups and the value of the Mann-Whitney U statistic.
VERT refers to vertical, LAT refers to lateral, Con refers to concentric.
*p value for the Mann-Whitney U test, before considering the false discovery rate adjustment
❖ denotes statistically significant differences at $p < 0.05$ after the false discovery rate adjustment.
► denotes a small effect size, ►► denotes a medium effect size, ►►► denotes a large effect size.

The average asymmetry index for each age group was less than 15% for both vertical and lateral force parameters (Table 3). The power parameters (vertical and lateral concentric power and the vertical and lateral average concentric power during the last 100 ms) had larger asymmetry indices than force parameters (maximum vertical and lateral force) for all age groups. These asymmetry indices varied between 5 and 32%. The maximum vertical and lateral force parameters had the lowest asymmetry magnitudes across all age groups. Asymmetry ranged from 2.5 – 5.8% for max vertical force. The 16U group represented the lowest asymmetry index for both vertical and lateral force. Asymmetry values for max lateral force ranged from 4.3% for the U16 group, to 13.8% for the U13 group.

Table 4.3 Mean (SD) Asymmetry Index (%) for each jump parameter, per each individual age group.

Age Group	VERT Avg Con Power	VERT Avg Con Power (100 ms)	LAT Avg Con Power	LAT Avg Con Power (100 ms)	Max VERT Force	Max LAT Force
10U	13.56 (8.37)	13.88 (7.30)	12.03 (5.92)	15.44 (3.28)	5.85 (1.48)	7.10 (1.83)
11U	14.22 (6.72)	19.46 (9.10)	13.47 (8.57)	13.44 (7.63)	2.80 (2.46)	7.14 (4.83)
12U	11.21 (8.47)	14.89 (10.23)	19.62 (11.02)	14.53 (12.45)	4.42 (3.62)	7.15 (4.53)
13U	14.58 (9.24)	15.19 (10.30)	17.92 (14.46)	13.60 (10.56)	4.71 (3.38)	13.84 (14.66)
14U	26.54 (14.59)	27.82 (15.50)	32.11 (19.75)	12.18 (9.72)	4.24 (4.11)	5.59 (4.89)
15U	16.53 (9.30)	10.63 (8.27)	13.24 (11.30)	8.45 (6.36)	4.68 (2.49)	6.05 (3.73)
16U	11.42 (11.25)	12.32 (7.25)	14.84 (14.30)	5.01 (4.08)	2.47 (2.55)	4.26 (2.27)

18U	17.55 (10.45)	12.33 (4.40)	29.51 (18.00)	13.21 (10.57)	5.01 (3.01)	7.85 (7.37)

VERT refers to vertical, LAT refers to lateral, Con refers to concentric.

4.4 Discussion

The purposes of this study were to measure normative single leg, medial countermovement jump parameters (i.e. maximum force, average concentric power and average concentric power during the last 100 ms) amongst youth ice hockey players, and to assess the interlimb asymmetry in these healthy athletes. These parameters were not significantly different between legs in our participants and therefore we defined our normative values based on the combined data set. We observed a general trend that these parameters increased with player age, and note significant changes between the 12U, 13U and 14U age groups, presumably related to physical maturation. Most asymmetries for these parameters were less than 15%.

In general, it appears as though body mass plays a critical role in jump performance [23]. Body mass is associated with improved peak power in adolescent boys and girls [23]. The 18U and 16U age groups had similar body masses, and they were much heavier compared to the 10U and 11U groups. The 18U age group outweighed the 10U group by an average of 40.3 kg.

Access to a structured strength and conditioning plan also affects jump performance. This differentially affected the athletes in this study. Athletes in the 13U-18U age groups participated in a structured strength and conditioning plan during the hockey season. Structured weight training has been shown to increase countermovement performance due to an increase in cross sectional area and muscle mass which leads to larger force output [24,25]. Accordingly, the fact that the younger age groups (10U-12U) did not partake in regular strength and conditioning sessions may have affected jump performance.

A large study reported increases in countermovement jump height between 10-11 year old, 12-14 year old and 15-17 year old males [26]. However, our data have greater granularity as we evaluated differences between yearly age groups (except for the 18U age group that included 17- and 18-year-olds). We observed the greatest number of differences between the 13U and 14U age groups. These age groups are at the peak height growth velocity for boys (13.85 ± 0.65 years old) [27]. During this age range tasks such as speed, static strength and power are related to the ages that an athlete matures [28]. The window of time between the ages of 13-14 showed the largest change in jump performance in our group of youth ice hockey players as five of six performance parameters had significant differences.

Finally, the asymmetry indices were the lower for the vertical and lateral force parameters compared to the power parameters. The average vertical asymmetry magnitudes for vertical force were 4.27% for all age groups, while the overall lateral force asymmetry was 7.37%. These asymmetries are consistent with previous research on elite youth soccer players [11]; however, that study calculated asymmetry of the jump height parameter measured with the “My Jump” iPhone application, and therefore may not be directly comparable. The soccer paper reports that asymmetry has important implications for performance as the degree of asymmetry in the single leg, countermovement jump was correlated with sprint times across various distances [11]. Vertical and lateral power asymmetries in the current paper were larger during the single leg, medial countermovement jump as magnitudes varied between 5.01% to 32.11%. These values are difficult to compare as normative power parameters for youth ice hockey players do not currently exist to the authors’ knowledge. Previous research on competitive male soccer players has evaluated asymmetry during countermovement jumps [29]. They suggest that asymmetries larger than 15% may be considered abnormal. However, it is important to note that they measured peak vertical force during countermovement jumps, and accordingly this threshold may not be relevant for the lateral force, vertical power and lateral power parameters that we report in this study. However, recent research has observed that asymmetry indices based on individual parameters do not accurately capture elements of jump strategy [30].

4.4.1 Limitations

There are limitations to this study. This study tested male youth athletes playing in a single youth hockey organization. Different organizations may have different resources such as strength and conditioning which may affect jump performance. In addition, female players should be tested to quantify normative differences between sexes. We included players of different playing positions which may have affected our results. Further research should evaluate whether there are differences in single leg, medial countermovement jump performance between player positions.

4.5 Conclusions

We determined normative values for parameters from the single leg, medial countermovement jump for male youth hockey players 10U-18U. This is an important performance test for monitoring strength and conditioning in hockey players. The normative data presented in this paper serves as a baseline for evaluating jump performance in youth hockey players. The single leg, medial countermovement jump allows the tester to measure ground reaction forces and power in the frontal plane which makes this test a relevant tool in all phases of sport performance and rehabilitation. To our knowledge, this is the first study to generate normative values of these jump parameters, and the first to investigate interlimb asymmetries in youth ice hockey players.

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Chapter 5

5 Discussion

This thesis identified current gaps in the injury literature for ice hockey, investigated a specific test that can be used to monitor and manage performance, and characterized key parameters for 10U to 18U players that may serve as a baseline measures for performance specialists to evaluate their athletes. This thesis reveled three main findings. There is a need for injury and athlete exposure to be defined consistently in ice hockey. However, all definitions of injury indicate that lower extremity injuries are prevalent in all levels of ice hockey, and knee injuries are particularly common. The single leg, medial countermovement jump may be used as a reliable tool for testing and monitoring ice hockey players as 12 parameters had moderate to excellent reliability. Finally, normative data suggests a general trend that force and power parameters from the single leg, medial countermovement jump increase with age.

Chapter 2 illustrated the need for a consistent definition of injury and athlete exposure. Establishing consistent categorical definitions is the first step in objectifying injury risks [1,2]. Several studies used injury definitions that specifically included concussions [3,4], one injury definition did not include overuse injures [5] , while others included dental injuries and fractures [4,6] and others did not [7,8]. We identified that the International Ice Hockey Federation (IIHF) definition of injury [9] based on time loss was the most appropriate. Their definition of injury is “An injury is considered reportable if a player misses a practice or a game because of an injury sustained during a practice or a game. The player does not return to the play for the remainder of the game following an injury; all concussions; all dental injuries; any laceration which requires medical attention; all fractures.” Although no definition can suit all needs, the time loss categorical definition provided by the IIHF is the most common and easiest to track across multiple leagues of play. As further support for the appropriateness of the time loss definition, it is the most common categorical injury definition used in team sports [1].

Chapter 2 also highlighted the need for a consistent athlete exposure definition. Athlete exposure has been calculated three different ways: games, player-game hours (based on a 60-minute hockey game), and total time on ice. The player game calculation (number of injuries/total number of players on the roster/number of games x1000) defines injury per 1000 player games and is based on the entire team roster. The player game-hours calculation, based on a 60-minute hockey game (number of injuries/number players on the ice at the same time/number of games x1000), defines the injury per 1000 player-game hours for players actively on the ice. However, researchers have used different roster numbers when calculating player hours, and total number of players actively on the ice when calculating player game-hours. Several studies have used both rosters [4,10], while others have used just one [3,11,12]. This has a direct effect as a larger number of players will lead to smaller injury rates. Finally, total time on ice (number of injuries/sum of individual AE time) has been used to quantify the athlete exposure definition in ice hockey [13]. This method is not simple to calculate as all leagues do not track player time on ice. Interestingly, the exposure differences were minimal between the time on ice metric and the estimated player game-hour metric, (14,676.2 hours calculated as the sum of players' time on ice versus 14,760 hours calculated as 30 teams x 82 games x 6 players on the ice). Therefore, the simplest way to calculate athlete exposure is to use six players on the ice and one hour per game (player-game hours). Using a consistent athlete exposure metric will improve the consistency and reliability of injury reporting, enabling comparisons between leagues.

Finally, Chapter 2 identified that lower-extremity injuries are prevalent in the sport of ice hockey, specifically MCL and ACL sprains [4,14-16]. In addition, hip related issues such as femoacetabular impingement (FAI), groin, soft tissue injuries [17] and intra-articulate hip injuries [18] are also prevalent. Based on the findings presented in Chapter 2, governing bodies such as Hockey Canada, USA Hockey and the IIHF should consider adopting consistent injury and athlete exposure definitions. In addition, with the large incidence of lower-extremity injuries sustained on the ice in youth [6,19,20], junior [21], collegiate [22], and professional [23] hockey, both performance coaches and physical therapists should focus on specific tests that serve to measure both performance and injury risk such as interlimb asymmetries.

Chapter 3 introduced a performance test called the single leg, medial countermovement jump. This test has been used in field based sports to assess performance [24], but is uniquely relevant to skating as the foot pushes laterally on the ice during propulsion [25]. The high face validity of this jump to the sport of ice hockey was identified in Chapter 3. Several temporal and kinetic variables have been measured in previous research [24]. Of these variables, eccentric and concentric peak forces and concentric peak power were the most reliable (ICC's: 0.86-0.96) among several other force and power metrics. In this thesis, a total of 12 vertical and lateral parameters were assessed for reliability. All force and power variables (lateral and vertical takeoff velocity, lateral and vertical maximal force, maximal force above bodyweight, lateral and vertical peak concentric power, average concentric power, and average concentric power during the last 100 ms of push-off) showed moderate to excellent reliability. This thesis extends previous research findings [24] and identifies that the single, leg medial countermovement jump is a reliable measure to assess force and power parameters in ice hockey players. A correlation matrix was used to identify relationships among variables in the single leg, medial countermovement jump. Near perfect correlations were observed between vertical concentric average power during the last 100 ms, and vertical peak concentric power (r = 0.99). A near perfect relationship was also observed for lateral concentric average power and lateral peak concentric power ($r = 0.99$). These near perfect correlations identified clusters of variables that were dependent. An inverse relationship between vertical takeoff velocity and lateral takeoff velocity ($r = -0.36$) was observed. This suggests a compromise between vertical and lateral components of the jump. Finally, low correlations were used to identify the subset of independent variables. A fair degree of independence between average and peak concentric power for both the lateral and vertical directions ($r = 0.58$; $r^2 = 0.33$ and $r = 0.63$; $r^2 = 0.40$, respectively) was observed.

In addition to having high face validity and moderate to excellent reliability, the single leg, medial countermovement jump provides objective measures of force and power as outlined in Chapter 4. This is important for rehabilitation and return to play timelines as injured athletes may demonstrate altered movement strategies. For example, ACLR patients demonstrated a significantly greater proportion of power on their operated hip [26], and an unloading strategy of the involved leg [27]. These individuals had an 18% lower sagittal plane energy absorption, compared to controls, on their involved leg nine months post-surgery during a bi-lateral drop jump task [27].

Given that the single leg, medial countermovement jump is a unilateral test, it is straightforward to calculate asymmetry indices since force is produced solely by the test leg. A recent review paper identified that unilateral tests potentially provide a more accurate representation of asymmetry for this reason [28]. Single leg force plate testing is a superior means of assessing jump performance than bi-lateral testing. However, force plates alone do not enable investigations into the movement strategy involved in single leg jumping and hopping-tests [49]. Research using three-dimensional motion analysis has observed significant asymmetries in movement strategy in individuals that have had anterior cruciate ligament reconstruction [29]. Specifically, the involved lower limb exhibited lower peak ankle dorsiflexion, and knee abduction angles during the single leg vertical hop test [29]. Other researchers have described the interaction of joints using the percentage of power generation at each joint during jumping [26]. Force plate testing does not enable this type of analysis; however, feasibly, practicality, total expense, and convenience also need to be considered.

Chapter 4 reported normative values of the single leg, medial countermovement jump in a group of 91 elite youth ice hockey players playing 10U, 11U, 12U, 13U, 14U, 15U, 16U and 18U level hockey. Other studies have examined normative values for the countermovement jump [30] and broad jump [31] in adolescents, but this thesis provides novel information regarding the performance parameters involved in the single leg, medial countermovement jump – a performance test that is particularly relevant for hockey. Six performance parameters were measured, including vertical and lateral maximal force, average concentric power and average concentric power in the last 100 ms. The results show a trend for the jump performance parameters to increase with age among the 10U-18U age groups. In addition, the 14U group was 23-30% greater than the 13U group for all parameters, and the differences for five of the six parameters were statistically significant - the largest number of significant differences between age groups. This age represents a heightened growth period in youth development where peak height velocity and puberty occur for boys [32]. Tasks such as speed, power and strength are related to physical maturity [33]. These normative values are an important as they may be used to compare other youth ice hockey players from various leagues and levels of play.

Interlimb asymmetries were also presented in Chapter 4. Interlimb asymmetries are expected in sports with preferred limb dominance [34]. Sports such as hockey do not have a dominant leg as propulsion requires equal contribution from both limbs. Findings from previous research has determined that an asymmetry measure between legs greater than 15% may increase the chance of injury [35-37]. Interlimb asymmetries may also affect sport performance as researchers showed that jump-height asymmetry of 12.5% from the unilateral CMJ was associated with slower linear speed and jump performance in academy youth female soccer players [38]. The average asymmetry index for each age group was less than 15% for both vertical and lateral force parameters. These numbers are consistent with previous research [38]; however, that study measured asymmetry in jump height measurements during single leg, vertical countermovement jump rather than the force and power parameters that we assessed. We observed that the maximum vertical and lateral force parameters had the lowest asymmetry magnitudes across all age groups; asymmetry indices ranged from 2.4 to 5.8% for maximal vertical force, and 4.2 to 13.8% for maximal lateral force. In contrast, the power parameters (vertical and lateral concentric power and the vertical and lateral average concentric power during the last 100 ms) had larger asymmetry indices than force parameters for all age groups. These asymmetry indices varied between 5 and 32%. To the author's knowledge, this thesis was the first to present both force and power asymmetries in the single leg, medial countermovement jump. The normative values for asymmetry may be used by performance and rehabilitation specialists to guide training with the goal of decreasing the risk of injury. Currently professional soccer teams employ an approach called player profiling [39]. This normative information is collected within the team and disseminated to coaches, sports science and sports medicine professionals on issues regarding injury status, availability and return to play. Normative values may also be used outside of the organization to compare reference values in other sports settings such as National Collegiate Athletic Association Division 1 sports [40].

The results of this thesis, in conjunction with other studies, can be used by rehabilitation and performance specialists to monitor, guide and assess performance and return to play initiatives. There is a need to continue to investigate alternative lower body testing measures in the sport of ice hockey as sport-specific functional performance tests requires careful consideration of safety, sport biomechanics, practicality and the athletes' current physical condition [41]. Finally, the test must be reliable and valid. The high degree of face validity and moderate to excellent reliability of the single leg, medial countermovement jump make it an excellent test for ice hockey players. Parameters of specific interest include lateral and vertical force, and concentric average power during the last 100 ms (each with ICCs between 0.86 and 0.98). Chapter 3 highlighted the single leg, medial countermovement jump parameters as being reliable for all 12 parameters measured. This may give rehabilitation and performance coaches confidence in the test itself.

In addition, the single leg, medial countermovement jump provides high face validity as both skating and the jump incorporate frontal plane force production - pushing laterally off one foot. Athlete's performances can also be compared to baseline measures of 10U-18U elite youth ice hockey players as presented in Chapter 4, enabling practitioners to establish rankings and monitor performance. This approach has been taken in field-based sports assessing jump strategy performance among soccer, rugby union and Australian rules football players [42]. In addition, the single leg, medial countermovement jump assesses interlimb asymmetry and enables the practitioner to evaluate readiness to return to play following a lower-extremity injury. This can be an important but difficult pursuit as significant inter-limb asymmetries can persist even after a player is cleared for sport [43]. Finally, monitoring the single leg, medial countermovement jump over the course of the season has been used to document player fatigue [44], and could also be used to document performance improvements or decrements such as jump height and asymmetry.

One limitation of this research was that it was not possible to perform on-ice performance tests. Therefore, we cannot conclude with certainty that the single leg, medial countermovement jump is related to on-ice skating performance. Research findings from AA and AAA ice hockey players observed that anterior to posterior horizontal leg power (off-ice sprint and 3 hop jump) was the best predictor of on-ice skating performance [45]. Future research should evaluate the relationship between the single leg, medial countermovement jump and on-ice skating performance tests. Three-dimensional motion analysis was not used in this thesis, and therefore some jump strategy variables and kinematics could not be measured. This is important as injured athletes may display movement compensations during testing [27,29]. In addition, all participants played in a single youth hockey league. Different organizations may have different resources such as planned, coached and organized strength and conditioning sessions that may affect performance [46]. The normative values were based on players of all playing positions (goalies, forwards and defensemen). The skating demands differ between player positions [47,48], and accordingly these normative values may not be adequate to describe different positions. Future research may be needed to determine if there are significant differences in jump performance metrics between player positions. Lastly, testing location may have affected performance. Testing took place at either a gym or an ice hockey rink. Different locations and temperatures may have altered physiologic behavior, causing a potential change in performance.

There were three main objectives for this thesis: 1) to systematically review the literature to determine which injuries are most common in ice hockey, and describe the inconsistencies in injury definition and injury rate, 2) to identify which performance test is most appropriate for elite youth ice hockey players, define meaningful parameters to describe the performance, and evaluate the reliability of these parameters in order to develop a subset of independent parameters, and 3) to describe the normative values for these parameters for a range of youth player ages. This thesis identified that lower-extremity injuries are common and costly in all levels of ice hockey, that the single leg, medial countermovement jump may be an appropriate performance test for hockey based on face validity and quantified the reliability of 12 performance parameters of and developed normative measures, including interlimb asymmetries, in 91 elite youth ice hockey players. These results provide evidence that the single leg, medial countermovement jump can reliably be used to test, monitor and manage performance in elite youth ice hockey players. Performance coaches, skill coaches and rehabilitation specialists can use this evidence-based test to monitor fatigue, assess performance and improve the return to play process from lower-extremity injury in ice hockey.

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Curriculum Vitae

Education:

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University of Western Ontario, London Ontario, Canada: PhD, January 2018-2021

- Currently pursuing PhD at University of Western Ontario (London, Ontario, Canada) school of Kinesiology
- Specializing in biomechanics and performance testing for competitive ice hockey players

MS, Exercise Science

California University of PA, California, Pennsylvania: Master's Degree December 2007

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- Specialization in Injury Prevention | Performance Enhancement & Health

BSc., Business Administration/Finance

Miami (OH) University, Oxford, Ohio: Bachelor of Science, December 2001

- Undergraduate degree in Business Administration from Farmer T. School of Business
- Played 4 years of varsity ice hockey – voted team assistant captain during 00-01 hockey season

Professional Experience:

Donskov Strength and Conditioning 2005-Present

Founder | Director of Sport Performance

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Head Strength and Conditioning Coach 2006-Present

Team USA Women's National Ice Hockey Team

Assistant Strength and Conditioning Coach July 2011-Jan 2016

Minnesota Wild, NHL

Development Camp Strength Coach July 2016

Anaheim Ducks, NHL

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Certifications:

- Certified by the National Strength & Conditioning Association as a Strength & Conditioning Specialist
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- Contributing writer for Michael Boyles's Strength Coach (www.strengthcoach.com)
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Research: Papers, Books and Conference Presentations

a) Published papers in refereed journals:

Donskov, A.S., J.S Brooks, and J.P. Dickey, *Reliability of the Single-Leg Medial Countermovement Jump in Youth Ice Hockey Players*. Sports, 2021. 9(5): p. 64.

Donskov, A.S., D. Humphreys, and J.P. Dickey, *What Is Injury in Ice Hockey: An Integrative Literature Review on Injury Rates, Injury Definition, and Athlete Exposure in Men's Elite Ice Hockey*. Sports, 2019. 7(11): p. 227.

b) Books

Donskov, A.S. *Physical Preparation for Ice Hockey II:, The Gain, Go, Grow Manual*. AuthorHouse: Bloomington, IN. 2020.

Donskov, A.S. *Physical Preparation for Ice Hockey I: Biological Principals and Practical Solutions*. AuthorHouse: Bloomington, IN. 2016.

c) Conference Presentations:

Donskov A, Humphreys D, Dickey JP. Injury in Elite Ice Hockey: Rate, definition, and athlete exposure. The Tenth International Hockey Conference. Halifax, NS, June 5-7, 2020 – cancelled due to COVID19 pandemic.

Donskov A, LeVangie MC, Hallihan A, Dickey JP. Relationship Between Skating Styles and Off-Ice Tests in Youth Hockey Players. The Tenth International Hockey Conference. Halifax, NS, June 5-7, 2020 – cancelled due to COVID19 pandemic.

Donskov A, Isometrics and program design. NSCA Hockey Conference. Colorado Springs, CO, June 7, 2018.

Donskov A, Strength and Conditioning For Ice Hockey. Okanagan Strength and Conditioning Conference, Kelowna, BC, Canada, July 2017.

Donskov A, Do No Harm. NSCA Ohio Conference, Columbus, OH, USA, May 2014, 2015.

Donskov A, Push/Pull Ratio for Contact Athletes. Dennison Strength and Conditioning Symposium, Granville, OH, USA, July 2012.

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Research: Grants

Dickey JP, **Donskov AD**. Prediction of skating style based on parameters derived from off-ice tests. Mitacs Accelerate (Industrial Partner: CCM hockey), 1 internship unit, 2020. $15,000 (submitted).