The Applied Use of Wearable Technology in Elite Female Ice Hockey

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ABSTRACT

Introduction: The use of wearable technology is increasing in the world of elite sport. The incorporation of evidence-based approaches to training has become a critical component in many competitive sports, including ice hockey. Despite its global popularity, ice hockey remains a neglected area of applied sport science research.

Objective: (1) To investigate the applied use of wearable technology in world-class female ice hockey; (2) build a strong foundation of applied literature using elite female subjects in an under-researched sport; and (3) provide information to sports science practitioners and coaches to better inform the preparation of athletes.

Methods: This study involved retrospective, secondary data analysis of four years of on-ice training and competition sessions from Hockey Canada's National Women's Team. Chapter three (Manuscript One) focuses on one full season of data and compares forwards and defensive players in various measures of internal and external load. Chapter four (Manuscript Two) uses data from one pre-season to investigate the differences in on-ice external load between sub-elite and elite female athletes. Chapter five (Manuscript Three) uses competition data to determine the differences in external load measures based on match outcome.

Results: The first major finding was that there were differences in both internal and external load measures between training and competition. Forwards had both higher volumes and intensities than defense in both training and competition. Furthering our understanding of the on-ice demands of training and competition, it was found that apparent differences exist between sub-elite and elite athletes in measures of external load. Elite ice hockey players had significantly higher measures for intensity-based measures of external load. The importance of on-ice intensity was additionally supported by examining external load measures in relation to match outcome. Among forwards, a significant difference was found for explosive ratio and percentage of high force strides.

Conclusions: This is the first study that investigated the use of wearable technology in elite female ice hockey. This data provides a solid groundwork for the continued pursuit of applied sports science in ice hockey. Each of the studies contributes to the existing evidence of athlete monitoring and athlete preparation using wearable technology and the study of elite female athletes.

DEDICATION

To Jack and Cole,

I hope you keep asking questions and searching for the answers – no matter your age.

ACKNOWLEGMENTS

To my wife Colleen and my sons Jack and Cole, thank you for all your support and love through both my academic and professional journeys. We have moved across the country and back again – and I could not have done it without you. To my parents, thank you for always providing me with an environment of support and challenging me to continue to grow and pursue excellence in everything that I do.

I would like to express my gratitude to my supervisor Dr. Alison Macpherson for her constant leadership and support. Alison was the one who first planted the seed to undertake this PhD and I am forever grateful of her being the first to see that I had it in me. Thank you for the encouragement every step of the way. To my committee members, Dr. Michael Rotondi, Dr. Joe Baker, and Dr. Veronica Jamnik, I could not have done it without you. Each of you brought your own area of expertise to the project that when combined, made it whole. Thank you for the mentorship and support throughout this journey.

Thank you to Hockey Canada for providing the data for use in this study. This work was born out of the conversations and planning sessions between many coaches and athletes that occurred in hockey arenas across the globe.

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LIST OF ACRONYMS

AIS – Australian Institute of Sport

ANOVA – Analysis of Variance

ARMSS – Applied Research Model for the Sport Sciences

COD – Change of Direction

CV – Coefficient of Variation

EE – Explosive Efforts

EE·min-1 – Explosive Efforts·min-1

ES – Effect-size

FIFA – Federation Internationale de Football Association

GPS – Global Positioning Systems

HR – Heart-Rate

HRmax – Maximum Heart-Rate

ICC – Intraclass Correlation

IIHF – International Ice Hockey Federation

IMA – Inertial Movement Analysis

MA – Motion Analysis

NHL – National Hockey League

PL – PlayerLoad

PL·min-1 - PlayerLoad·min-1

RPE – Rating of Perceived Exertion

SD – Standard Deviation

SEE – Standard Estimate of the Error

SEM – Standard Error of Measurement

sRPE – Sessional Rating of Perceived Exertion

TEM – Typical Error of Measurement

TMA – Time-Motion Analysis

TRIMP – Training Impulse

USA – United States of America

VO2 max – Maximal Aerobic Oxygen Consumption

CHAPTER 1: INTRODUCTION

1.1 Applied Sports Science in Elite Sport

In the pursuit of continued athletic improvement, many athletes, coaches, and teams are turning to the science field to improve performance. This has led to the creation of the field of sports science. Sports science is a multi-disciplinary field that aims to answer questions surrounding the understanding and enhancement of sporting performance (Bishop, 2008). Applied sports science is about applying the best available evidence at the right time, in the proper setting, for the individual or team to improve their performance.

The incorporation of evidence-based approaches to training has become a critical component in many competitive sports, including ice hockey. This change is reflected in the integration of sports science experts (analysts, medical teams, and researchers) as well as increased use of technology to help increase scientific rigor (Balagué, Torrents, Hristovski, & Kelso, 2017; Paul & Ellapen, 2016). The inclusion of wearable technologies (also known as 'wearables'), such as heart-rate (HR) monitors, global positioning systems (GPS), and accelerometers, has become common in many elite sport programs. First utilized for athlete tracking in 1997, GPS and accelerometer technology are increasingly used in team sport settings to provide practitioners with comprehensive and real-time analysis of player performance during training or competition (Cummins, Orr, O'Connor, & West, 2013). The use of wearables may enhance coaches' decision-making practices while also helping to optimize player performance (Collins, Carson, & Cruikshank, 2015). Training interventions, tactical assessments, competition preparation, and athlete feedback are just some of the areas influenced by the incorporation of wearable technologies in sport programs (Carling, Wright, Nelson, & Bradley, 2014; Jones & Denison, 2018; Mackenzie & Cushion, 2013).

The application of sports science in the sporting environment, while widely regarded, is not without challenges, especially when it comes to coach implementation. Research has shown that sports science allows coaches to make effective decisions and solve problems (Abraham, Collins, & Martindale, 2006). Coaches do believe that sports science can contribute to coaching and have an interest in finding new and innovative ways to improve their team through the application of sports science (Reade, Rodgers, & Spriggs, 2008). However, when the learning process of elite coaches has been investigated, the dominant form of coach education comes from the interaction with other coaches, not from sports scientists (Irwin, Hanton, & Kerwin, 2004).

Many identified factors contribute to this lack of transfer, including conservative coaching practices, outdated coaching education, and lack of confidence in the research methods (Bishop, 2008; Martindale & Nash, 2013). A leading assumption regarding the lack of applied sports science is that those in decision-making positions (coaches and management) do not perceive research findings as relevant to their practice (Bishop, Burnett, Farrow, Gabbett, & Newton, 2006). For sports science to continue to grow and succeed, there is a need for representation in the literature of all sports, which would allow coaches to directly access pertinent information about their sport, regardless of gender or sport of choice.

While coaches indicate that there is value in the application of sports science practice in sport, it is evident that there is still a gap between translating sports science to practice and game preparation (Bishop, 2008). Much of the team-based applied sports science research literature is heavily influenced by non-North American team sports such as soccer/football, rugby, netball, cricket, and Australian Rules Football. It is hypothesized that one reason behind the Australian-dominated applied sports science field is the strong relationship between the Australian Institute of Sport (AIS) and Universities where sports science researchers are embedded with sports coaches. Significant funds were directed to elite athlete programs and sports science research at institutes of sport, often in conjunction with university programs (Williams & Kendall, 2007).

Even though those involved in high-level sport have recognized the importance of sports science, it has not been fully embraced as a means of translating research into practice. In response to this identified gap, Bishop (2008) has proposed a model that can be used to guide the direction of research required to build an evidence base around the application of sports science research to influence performance. The Applied Research Model for the Sport Sciences (ARMSS), provides a framework from which researchers can use to integrate their applied research in sport through a logical progression (Figure 1.1).

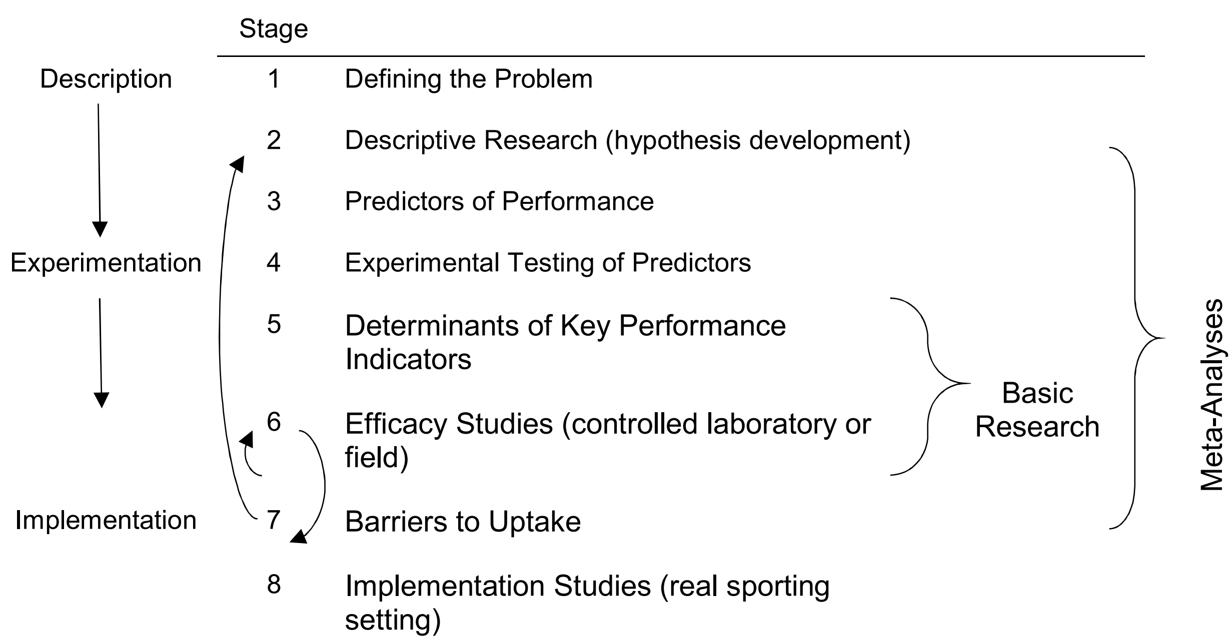

Figure 1.1 – An applied research model for the sport sciences (Bishop, 2008).

Within the scope of this dissertation, the ARMSS provides a framework from with to build an area of research that currently does not exist, as there is little previous research into the use of wearable technology to measure the work performed in ice hockey, while also focusing on producing literature using elite female athletes. By using the model, the goal is to impact the research field in a logical progression, allowing for future work to build off the concepts developed from this project.

The first stage of the model is to define the problem that needs to be answered or the identified gap in the sport or research literature. It is recommended that researchers identify the problems and issues that coaches and athletes face (Bishop, 2008). Within ice hockey, there is little research that measures the physical work that players are performing during practices and games. Research has focused on HR-based metrics such as time spent at certain percentages of maximum HR (Green, Bishop, Houston, McKillop, Norman, & Stothart, 1976; Hoff, Kemi, & Helgerud, 2005; Jackson & Gervais, 2016; Montgomery, 1988) or estimates of intensity and movement demands based off time-motion analysis (TMA) (Akermark, Jacobs, Rasmusson, & Karlsson, 1996; Green et al., 1976, 1976; Jackson & Gervais, 2016; Lafontaine, Lamontagne, & Lockwood, 1998). With the increased use of wearable technology to measure the work performed in other sports, there is no research applying this technology in the sport of ice hockey. The lack of information available surrounding the use of wearable technology in ice hockey presents an opportunity to produce innovative research that can be the cornerstone for future works.

Stage two of the ARMSS model progresses from defining the problem to producing descriptive research. Descriptive research is crucial for underpinning future stages of the ARMSS (Bishop, 2008). The need for high-quality descriptive studies can help bridge the gap between sports scientists and coaches. Descriptive research can feed valuable information back to the coaches to further the athlete preparation plans across all domains. Optimal performance at the highest stages requires integration of not only the physiological elements of competition but also of the psychological, technical, and tactical components (Smith, 2003). Each of these components needs to work to complement each other at the time of competition for optimal performance. Any training, be it practice, competition, or physical, imposes stress onto the athlete. These stressors and the exposure to these stressful environments need to be coordinated for peak performance to occur. Optimal training and performance development depend heavily on the ability to integrate and react to as many relevant variables as possible (Smith, 2003).

Training load is one factor in the holistic model; however, it has been identified as the factor most easily modifiable in relation to the variations in the total stress experienced by athletes in their preparation and performance. Descriptive research provides the sports scientists and the coaches with normative data to compare training loads and allow them to adjust for their teams during both the preparation and competition phases of performance.

The third stage of the ARMSS builds off the foundational research built in the previous stages. Stage three is called "Predictors of Performance" and aims to understand factors of performance (Bishop, 2008). This stage is accomplished through research that begins to explore relationships between performance variables. Stage three hinges on the identification of factors that could potentially be modified to improve actual sport performance. Sports analytics have become a serious adjunct to sports such as ice hockey; thus, the combination of in-game player monitoring metrics alongside traditional hockey analytics could provide a wealth of predictive information for future studies. This information can be used by sports scientists, sport coaches, and athletes to advise both preparation and performance in relation to sport results as there is no more significant measure of sporting success than match outcome. It is important to bear in mind that the variability of sport can never be truly controlled, and therefore such studies can only yield important indications of those factors that could potentially be modified to improve actual sports performance (Bishop, 2008).

A large amount of external load research is descriptive, through the detailing and comparison of external load between various activities. The benefit of these studies is that they provide methods to quantify and analyze external load, while also allowing practitioners to have a deeper understanding of the performance demands of athletes (Cardinale & Varley, 2017). The dearth of applied sports science literature, specifically surrounding wearables, has placed the applied sports scientist working in ice hockey at a disadvantage. There is a need for peer-reviewed works to advance both the field and sport, as it has in other team-based sports where the use of an applied sports scientist is commonplace (Martindale & Nash, 2013). Furthermore, sports science information forms a significant part of the knowledge-base required for coaches to make effective decisions and solve problems (Abraham et al., 2006). Furthering the applied knowledge in the field could lead to further innovation of the sport and provide different opportunities for more integration of sports science and coaching in ice hockey.

In addition to the need for applied sports research in ice hockey, this collection of works focuses on elite female athletes. Female athletes are an under-represented cohort in many research studies, as is research based on true elite athletes. Based on a review that investigated the use of integrated technology such as GPS and accelerometers in team sports, less than half of the papers included female subjects (Dellaserra, Gao, & Ransdell, 2014). Similarly, in a review surrounding the use of wearables to quantify sport-specific movements performed by Chambers and colleagues (2015), only 10 of the 28 papers included in the review contained female athletes as subjects (Chambers, Gabbett, Cole, & Beard, 2015). Ice hockey was not represented in either study, which both reviewed current practices in high-level team sport.

Research involving actual elite athletes is rather rare. However, in sports science literature, elite is a term used liberally, and often misapplied to studies involving athletes that participate at a high level. It is not uncommon for the term elite to describe athletes who are moderately trained, highly trained, or refer to a group of athletes consisting of both high and low-level athletes (Charness & Schultetus, 1999; Sands et al., 2019). A taxonomy proposed by Baker and colleagues (2015) delineates the categorization of athletes based on the various stages of skill acquisition. They provide a clear framework to define the athlete categories, where an expert athlete is one who performs two standard deviations from the mean performance for the population or within the top five percent of performance (Baker, Wattie, & Schorer, 2015). The use of categorization criteria sets a clear delineation from other levels of skill and competition, including the reference of "advanced" to reflect athletes who play at national levels of competition or high levels of intercollegiate competition. (Baker et al., 2015). In the sports science literature, terms such as expert and elite are used interchangeably; therefore this paper will refer to athletes at the highest level of their sport (international competition) as "elite", and athletes of a lesser level of play as "sub-elite".

1.2 Specific Objective

The specific objective of this dissertation is to address the gap in knowledge around performance of elite female athletes using wearable technology. The use of wearable technology in sport is growing, and ice hockey is an underrepresented sport in this area of research regarding training and competition demands, the use of technology to evaluate and track athlete progression over time or between groups, and to measure progress that is translatable to performance. Sports science has been criticized for disseminating findings that are too difficult to apply, failing to answer relevant questions, or promoting research that lacks applied relevance

(Martindale & Nash, 2013). Based on the structure of the project, this body of work will impact both the applied research in the sport of ice hockey and can provide information that could be used by sport coaches. Lastly, it will increase the representation of female athlete-centric research in sport.

CHAPTER 2: LITERATURE REVIEW

2.1 Ice Hockey Demands

Ice hockey is a sport characterized by athletes performing repeated bouts of high-intensity efforts of maximal power interspersed with periods of low-intensity movements. High-performing ice hockey athletes must have well-balanced physical and physiological systems including robust anaerobic fitness (Wilson, Snydmiller, Game, Quinney, & Bell, 2010), high aerobic fitness (Burr et al., 2008), and a blend of muscular strength, power, and endurance (Ransdell & Murray, 2011). These physical characteristics need to complement sport-specific skills such as skating, shooting, and passing of the puck (Twist & Rhodes, 1993).

Using TMA of a hockey game to determine physical demands, Green and colleagues (1976) showed that forwards averaged between 14 to 21 shifts per game depending on their shift deployment. Typical shift length was 85 seconds of total time, with an average of 20 minutes total time on ice (Green et al., 1976). Of those 85 seconds of shift length, 39 seconds consisted of actual playing time of mixed levels of intensity; however, the average HR was approximately 80% of a player's maximal aerobic power (Green et al., 1976). Similar results were found by Montgomery (1988), where ice hockey athletes recorded an average HR of 85% of their maximum HR (HRmax) while on the ice (Montgomery, 1988). Within the shifts themselves, the pace of play and movement did not occur at a constant speed or intensity. Players are afforded brief recovery periods during whistle breaks for penalties or stoppages of play, and when performing at low or moderate intensities, such as gliding or standing still (Nightingale & Douglas, 2018). Research by Stanula and Rocziok (2014) reported in-game HR by position and found that defensive players spent 22% of their playing time with HR exceeding 94.5% of their

HRmax, and 22% of the time between 82.6 and 94% of HRmax. Forwards spent 19% of their time greater than 94.5% and 26% in the moderate-intensity zone (Stanula & Roczniok, 2014).

Many attempts have been made to quantify the energy demands during a game, with research supporting that ice hockey players rely heavily on their anaerobic system. It has been found that over two-thirds of energy demand is met through the anaerobic glycolytic system (Green & Houston, 1975; Seliger et al., 1972). Due to the discontinuous gameplay, the aerobic system is essential for the recovery of the energy systems during breaks in play (Lau, Berg, Latin, & Noble, 2001). A strong relationship has been established between maximal aerobic oxygen consumption (VO_2 max) and success during gameplay (Green, Pivarnik, Carrier, & Womack, 2006). Previous research found that elite male ice hockey athletes have recorded VO_2 max values between 50-60 $ml \cdot kg^{-1} \cdot min^{-1}$ (Twist & Rhodes, 1993a). Collegiate female ice hockey athletes have a lower VO_2 max, with a range of 40-50 $ml \cdot kg^{-1} \cdot min^{-1}$ (Carey, Drake, Pliego, & Raymond, 2007; Durocher, Arredondo, Leetun, & Carter, 2008).

In addition to robust aerobic and anaerobic systems, ice hockey athletes must have adequate levels of muscular strength, power, and endurance to perform. Stronger athletes can skate faster and apply more force with each stride into the ice (Mascaro, Seaver, & Swanson, 1992). High-level male skaters who exhibit an ability to create high levels of horizontal leg power were faster and more agile during skating tests (Farlinger, Kruisselbrink, & Fowles, 2007). Likewise, elite male hockey players with higher vertical jump scores were drafted higher than their peers who expressed lower levels of leg power (Burr, Jamnik, Dogra, & Gledhill, 2007). Jumping, similar to skating, requires coordination of the upper and lower body to propel forward at high velocities, and it is hypothesized that the vertical jump best simulates these full-bodied coordinated movements (Burr et al., 2007). Upper body strength is vital as it allows athletes to shoot harder, use their body for positioning and body contact with another person or the boards (Twist & Rhodes, 1993a). Upper and lower body strength have been shown to have a positive impact on in-game statistical measures. In collegiate male ice hockey players, higher levels of strength measured in the preseason resulted in a more favourable plus/minus (+/-) at the end of the season (Peyer, Pivarnik, Eisenmann, & Vorkapich, 2011). Plus/minus is a rudimentary statistic hockey coaches use to measure a player's impact on the game. While a player's plus/minus score is calculated for each game played, it tends to provide a more meaningful measure over a full season. The statistic is influenced by both the offensive and defensive performance and is directly affected by overall team performance.

Recently, optical tracking technology has been developed to measure and monitor locomotive outputs during gameplay. A study by Lignell and colleagues (2017) analyzed one National Hockey League (NHL) match. They report that there was a clear demarcation of movement demands between forwards and defense. The defense had more volume of work; they covered 29% more total skating distance with 47% more ice time. On the other hand, forwards had more density; they covered 54% more high-speed distance per time on ice (Lignell, Fransson, Krustrup, & Mohr, 2018). These differences between attacking and defending players are somewhat different from many other sports who have tracked this type of locomotion. In sports like soccer, rugby sevens, and rugby union, the positional group that accumulates greater high-speed running tends to cover more total distance through a match (Burgess, Naughton, & Norton, 2006; Di Salvo et al., 2007; Quarrie, Hopkins, Anthony, & Gill, 2013; Suarez-Arrones et al., 2014). The movement patterns of ice hockey defensemen seemed to relate more closely to defenders in handball, likely due to a similar pace of play as well as a similar-sized playing surface compared to the larger playing fields in rugby and soccer (Povoas et al., 2014; Povoas, Seabra, Ascensao, Magalhaes, Soares, & Rebelo, 2012). While suggested that forwards emphasize repeat-sprint ability in training, defenseman appears to require the capacity to work across all aspects of aerobic and anaerobic metabolism.

2.2 Female Ice Hockey Characteristics and Participation

Elite women's ice hockey is governed by the International Ice Hockey Federation (IIHF). It hosts two major tournaments, the Women's World Championship (which runs every year for three years) or the Winter Olympic Games (every fourth year). The IIHF has hosted 18 championships during non-Olympic years, with Canada winning ten times. Women's hockey debuted in the Olympics in 1998, with Canada winning 4 out of 6 gold medals during this time, with the United States of America (USA) winning the other two gold medals (IIHF, 2018).

Female hockey has seen significant growth over the last thirty years, both at the grassroots level as well as on the international stage. Women's hockey participation rates in North America have experienced a growth of over 1000% during that time, from approximately 6,000 in 1990 to 79,355 in 2019 in the USA (USA Hockey, 2019) and from 8,146 in 1990 to 83,711 in 2018 in Canada (Hockey Canada, 2018). At the international level, the participation rate of female ice hockey is growing, as there are now 36 countries that are participating in various divisions of the IIHF (IIHF, 2019). Women's hockey has representation in every part of the world with teams in North America, Europe, Asia, Oceania, Africa, and Latin America.

2.3 Elite Female Ice Hockey Definition in Literature

Research involving elite female ice hockey athletes suffers due to the lack of consistent terminology and classification. It is not uncommon to find research that labels Canadian University players as elite (Geithner, Lee, & Bracko, 2006). Based on standardized classifications of elite and sub-elite athletes (Baker et al., 2015; Lorenz, Reiman, Lehecka, &

Naylor, 2013), Canadian University hockey is not an accurate representation of elite athletes. Only two studies defined an elite female ice hockey player with reference to international-caliber athletes at the highest level of their sport. A paper by Ransdell and Murray (2011) published profiles of pre-competition fitness testing data of American female ice hockey players before the Vancouver Olympics (Ransdell & Murray, 2011). The second paper studied the physical fitness characteristics of elite female hockey teams at an IIHF multi-national training camp (Ransdell, Murray, & Gao, 2013). This study analyzed the results by comparing developmental athletes from programs of countries who are consistently at the top of the podium and achieve continued success in female hockey (Canada and USA) compared to athletes from lower-ranked hockey nations. Athletes from North America would be considered elite; however, these athletes are still at a developmental age (under-18), and therefore still have the potential growth of their physical and physiological development.

2.4 Methods to Quantify Athlete Movements

The dominant method to measure on-ice work in hockey research has been TMA. Time-motion analysis involves setting up video recording equipment, monitoring players' movements, and categorizing them according to their intensity. The TMA method has been widely used across many team sports (Abdelkrim, El Fazaa, & El Ati, 2007; Gabbett & Mulvey, 2008; Green et al., 1976; Matthew & Delextrat, 2009; Spencer, Lawrence, Rechichi, Bishop, Dawson, & Goodman, 2004), but is often criticized when applied to sports where player movements are highly explosive and short in duration, thus making them difficult to record accurately (Nightingale & Douglas, 2018). Reliability of TMA is often dependent on the observer, and therefore can vary significantly based on the number of observers, the expertise of the observer, and the level and sport observed (Duthie, Pyne, & Hooper, 2003). There is no standardized level of expertise required to partake in TMA, and as such, the main limitation of this form of analysis is inter-observer reliability (Dobson & Keogh, 2007). Another limitation of TMA is that it cannot provide real-time information regarding the context of movement, which sport coaches and applied researchers have found beneficial (Dellaserra et al., 2014).

To quantify the movement demands of female ice hockey, Jackson and colleagues (2016) analyzed three different games of women's collegiate ice hockey. They found that the movement demands were similar to those of male ice hockey players, whereby the majority of on-ice movement is classified as low to moderate intensity forward gliding. Positionally, the forwards were found to skate at a higher intensity for longer durations than defensive players (Jackson & Gervais, 2016). This is the only study to date that attempts to quantify the movement demands of female ice hockey players. The researchers utilized TMA to do so, and readily mention that TMA can be questioned based on its reliability and subjective nature of classification.

A solution to objectively measure the movement demands in sport has been to outfit athletes with wearable technology. The wearable technology field has seen rapid growth over the last ten years, as companies have rushed to meet the demands of athletes and consumers (Düking, Hotho, Holmberg, Fuss, & Sperlich, 2016). Wearables are appealing to athletes due to the non-invasive nature as they are small, lightweight, and worn close to the skin (Halson, Peake, & Sullivan, 2016). The use of wearable technology has been widespread in many outdoor sports as most units include a GPS unit, accelerometer, gyrometer, and magnetometer. In field-based sports, wearable technology has been used to objectively measure movement demands, assess the differences between practice and competition demands, and provide information regarding explosive movements and high-intensity movements (Dellaserra et al., 2014).

The use of wearable technology consisting of sensors that combine accelerometers, gyroscopes, and magnetometers to identify sport-specific movements are commonplace in a variety of individual and team sports (Chambers et al., 2015). This information has been used to quantify the work athletes are doing across a myriad of sports, including those both on land and in the water. For example, the use of wearable technology has been used by swimmers to provide automated feedback of strokes to the coaches on the pool deck, thus allowing them to provide immediate objective feedback to the athlete while they are training (Magalhaes, Vannozzi, Gatta, & Fantozzi, 2015). Similarly, in a team sport example, the physical demands measured from GPS units increased over five years in Australian Rules Football; athletes were required to run faster at greater distances, and at a higher intensity for a longer duration (Wisbey, Montgomery, Pyne, & Rattray, 2010). Sport practitioners have also used wearable technology to determine the positional differences of athletes on the same team. In cricket, fast bowlers sprinted twice as often, covered three times the distance, and had a shorter work-to-rest ratio when compared to other positions on the pitch (Petersen, Pyne, Dawson, Portus, & Kellett, 2010). This information is invaluable to the athlete, coach, or sport practitioner as they can adjust the daily or weekly plan before, during, or after practice to better aid and assist in the performance of both the individual athletes and the team.

Due to the indoor nature of ice hockey, the use of GPS devices is not applicable to measure the movement demands of players. However, there is promising research that technology incorporating triaxial accelerometry, along with the recordings of the gyroscope and magnetometer, can successfully quantify sport-specific movements. One such method to quantifying the workload exerted by an athlete is to sum the individual triaxial accelerometer vectors to produce an arbitrary unit of measure known as PlayerLoad. PlayerLoad is calculated by using the measurements recorded via a MinimaaX™ unit (Catapult Sports, Melbourne, VIC, Australia). It is defined as an instantaneous rate of change of acceleration divided by a scaling factor utilizing the accelerometers within the three planes of movement to quantify movement intensity (Boyd, Ball, & Aughey, 2011). PlayerLoad has been used to describe the physical demands of sports such as Australian rules football (Boyd, 2011), basketball (Heishman et al., 2018; Montgomery, Pyne, & Minahan, 2010), netball (Chandler, Pinder, Curran, & Gabbett, 2014; Cormack, Smith, & Mooney, 2014), rugby (Gabbett, 2015; Hulin, Gabbett, Johnston, & Jenkins, 2018; Quarrie et al., 2017), cricket (McNamara, Gabbett, Chapman, Naughton, & Farhart, 2015; McNamara, Gabbett, Naughton, Farhart, & Chapman, 2013), and soccer (Dalen, Jorgen, Gertjan, Havard, & Ulrik, 2016). Before the undertaking of this dissertation, there was a singular paper published that has investigated the use of PlayerLoad in ice hockey. Van Iterson and colleagues (2017) examined the test-retest reliability of PlayerLoad during nine ice hockey tasks in a simulated game-like condition. The MinimaaX™ unit, also known as the Catapult S5 (Catapult Sports, Melbourne, VIC, Australia), was worn by eight male collegiate ice hockey players and measured PlayerLoad during skating tasks which included forward and backward acceleration-based skating, low-intensity gliding, cross-overs, and slap shots. They reported moderate-to-large test-retest reliability when using PlayerLoad to quantify on-ice movements (CV 2.2-13.8%) (Van Iterson, Fitzgerald, Dietz, Snyder, & Peterson, 2017).

2.5 Validity and Reliability of Catapult S5 Units

The most important consideration for the use and implementation of technology within the applied sport science field is the validity and reliability of the technology. The validity of a unit reflects the ability of the unit to accurately measure what it intends to measure (McDermott, 2009). Measures of validity are presented as the standard estimate of the error (SEE), standard error of measurement (SEM), coefficient of variation (CV), or the percentage of difference of the mean from criterion measures (Scott, Scott, & Kelly, 2016). According to previous research evaluating the relative error of accelerometer-based devices a CV ≤5% are considered as small, CV ≥5% and <20% as moderate and CV ≥20% as large (Alexander et al., 2016; Wundersitz, Gastin, Robertson, Davey, & Netto, 2015). Based on previous research, it is best practice for accelerometer-based sensors in the field to have a CV <20% (Tran, Netto, Aisbett, & Gastin, 2010; Wundersitz, Gastin, Richter, Robertson, & Netto, 2015).

The second important consideration for technology is reliability. Reliability refers to the reproducibility of values on repeat occasions (Hopkins, 2000). Reliability is important for practitioners when they compare session-to-session changes (intraunit) or between different players (interunit). Measures for reliability are presented as CV, typical error of measurement (TEM), or intraclass correlations (ICC) (Scott et al., 2016). Reliability can be rated as good (<5%), moderate (5-10%), or poor (>10%) (Duthie et al., 2003).

Several validation studies have been performed on the Catapult S5 unit, both on the unit components, as well as the metrics it provides. Laboratory-based validation studies have been performed using specialized equipment meant to provide a controlled testing environment to test the validity of the devices. Nicolella and colleagues (2018) used a special electrodynamic shaker table capable of generating controlled oscillations at frequencies up to 20 Hz. The devices were subjected to a series of oscillations in each of three directions; front-back, side-to-side, and up-down. The devices have been found to have an excellent intradevice reliability for PlayerLoad values, with most CV values <1.0%. It is reported that Intraclass Correlation Coefficient (ICC) ranged from 0.8 to 1.0 for intradevice comparison (Nicolella, Torres-Ronda, Saylor, & Schelling, 2018).

A second group tested the Catapult S5 device against a 3D motion analysis (MA) system to determine the validity of the filtering used on the accelerometer data. In clinical gait laboratories, MA systems are the gold standard measure used to accurately describe the kinematics of motion (Elliott & Alderson, 2007). Using the Vicon Motion System, the researchers performed standardized movement simulations while inside the capturing space of the Vicon system while wearing the S5 device. They report CVs <5% when comparing the filtering used on the accelerometer-based data with the data collected on the MA system (Roell, Roecker, Gehring, Mahler, & Gollhofer, 2018). In a secondary analysis using the accelerometer data in an MA system, the accelerometer contained within a wearable tracking device demonstrated an acceptable level of concurrent validity compared to an MA system when filtered at a cut-off frequency of 12Hz. This result advocates the use of accelerometers to measure accelerations in team sports as most units sample below this cut-off (Wundersitz, Gastin, Robertson, et al., 2015).

The reliability of the Catapult S5 devices has also been tested, both in the laboratory and under field conditions. The Catapult devices generally showed excellent intra-device reliability with the majority of within device CVs less than 2.0% (Nicolella et al., 2018). Using a similar laboratory set-up as previously mentioned studies, Boyd and colleagues used a hydraulic testing machine to oscillate devices at specified acceleration ranges, and found the devices to have within- and between- device CVs of 1.0% (Boyd, Ball, & Aughey, 2011).

Van Iterson and colleagues examined the test-retest reliability of PlayerLoad during nine ice hockey tasks in a simulated game-like condition. Using eight Division 1 male collegiate ice hockey players, they performed nine distinct skating tasks to simulate the movements that players undergo during gameplay. Those nine tasks were: forward acceleration, backward acceleration, forward top-speed, backward top-speed, moderate speed, coasting, repeated-shift, slapshot, and bench sitting. They found the ICC for eight of the tasks was >0.75 (very large), with the forward acceleration task falling within the moderate range (0.4-0.59) (Van Iterson et al., 2017).

Another component of the Catapult S5 devices is the ability to use inertial movement analysis (IMA) to measure multi-planar explosive movements. High-intensity movements in ice hockey include rapid accelerations and decelerations, high-intensity skating, rapid changes of direction (skating-based or body contact), and high-intensity shots. For an event to be recorded by the IMA, a polynomial least-squares fit is applied to the X, Y, Z resultant acceleration data and smoothed at a known frequency. This smoothed trace is overlaid with the original acceleration trace, and the start and end-point of the event were identified. Once identified, the sum of the X, Y area was calculated and expressed as the event magnitude ($m \cdot s^{-1}$) (Innovations, 2013). Identified movements occurring at a rate higher than 2 $m \cdot s^{-1}$ in any direction is identified and counted (Dalen et al., 2016; Meylan, Trewin, & McKean, 2017). Using world-class female soccer players, it has been determined that IMA data can detect maximal acceleration, deceleration, and change of direction (COD) during maximal effort suggests that this metric could represent a new method to quantify a count of match-specific explosive actions given its match-to-match variability (Meylan et al., 2017).

2.6 The Application of Wearable Technology in Sport

The primary use of wearable technology in sport is to monitor and manage training load. Monitoring training load provides sport practitioners, whether that is coaches, sport scientists, or the athlete themselves, information regarding how their athletes are responding to the daily workload performed during practices and competitions. By monitoring an athlete's training load, practitioners gain clearer insight about the sport's demands; information that can be used to design the athlete's training program to match the actual demands of the sport better.

Training load is categorized into internal load and external load. Internal training load is defined as the relative biological stressors imposed on the athlete during training or competition (Bourdon et al., 2017). The most commonly used metrics for measuring internal load include HR and HR-related metrics (Borresen & Lambert, 2009), rating of perceived exertion (RPE) and sessional rating of perceived exertion (sRPE) (Chen, Fan, & Moe, 2002); as well as typical lab-based measures such as blood lactate and oxygen consumption (Bourdon et al., 2017). External training load is the objective measure of the work performed by the athlete during training and competition (Wallace, Slattery, & Coutts, 2009). Standard external load metrics include power output, speed, acceleration, TMA, GPS-derived parameters, and acceleration-derived parameters (Halson, 2014). Monitoring external load provides quantifiable information about the workload performed during the session, and internal load provides information as to how the athlete is responding to the workload from a physiological perspective.

The most applicable methods of load monitoring successfully evaluate physiological changes and assess movement patterns and indicators of skills specific to the sport (Halson, 2014). The combination of internal and external load monitoring metrics can provide a wealth of knowledge to aid in the decision-making process of how to progress or regress athlete preparation. By monitoring internal and external load, practitioners gauge how an athlete is handling the training volume and intensity before determining appropriate loading strategies for subsequent days of training (Akubat, Barrett, & Abt, 2014; Gabbett et al., 2017; Halson, 2014). For example, two athletes who have the same external load for the same drills and duration may record different internal loads from HR measures due to individualized fitness or fatigue factors.

Factors that could influence the variability in response to the imposed external loads may include age, sex, current fitness level, or training frequency (Borresen & Lambert, 2009; Bourdon et al., 2017). Monitoring the individual can allow for sport science practitioners and coaches to better prescribe loads that are suitable for both the team and athlete.

Applied sport practitioners have found both positive improvements in injury rates (Hulin, Gabbett, Caputi, Lawson, & Sampson, 2016) and performance (Borresen & Lambert, 2009) with a smart application of load. In both cases, this was accomplished through systematic dosing of external load and tracking the response of internal loading metrics. Through the practice of monitoring load, practitioners attempt to determine the optimal balance of training intensity and volume, as well as the athletes' response to the imposed demands, to impact performance in games positively. This dose-response relationship is essential, as athletes fluctuate between fitness and fatigue, and optimizing the volume and intensity of subsequent load is vital for continued performance (Busso, 2003). The application of this relationship can provide information to improve future training (Racinais et al., 2014), identify fatigue during competition periods (Akubat et al., 2014), and identify changes in athlete performance in a competition (Buchheit et al., 2013).

The use of an objective monitoring system, whether it be internal or external, is valuable to both athletes and coaches. Monitoring load is important because each athlete can have a different response to training, but also coaches and athletes perceive the intensity of practices and game differently. Brink and colleagues (2014) found that there was a discrepancy between the prescribed intensity of practice between these two groups, where athletes perceived the intensity and training load of practice as significantly more challenging than what was intended by the coaching staff (Brink, Frencken, Jordet, & Lemmink, 2014). This difference between coaches and athletes has been shown in other sports such as judo (Viveiros, Costa, Moreira, Nakamura, & Aoki, 2011), volleyball (de Andrade Nogueira et al., 2014), and tennis (Murphy, Duffield, Kellett, & Reid, 2014). Throughout a season, these differences could lead to a maladaptation to training and underperformance, which is an undesired outcome for both coaches and athletes alike.

The sophistication of metrics used by sport practitioners has improved in tandem with the improvements in technology. While distance covered is still one of the more popular external load metrics to track, other important metrics identified in the literature being applied in sports are work rate (metres per minute), time spent in high-intensity work ranges, and total distance covered (Taylor, Chapman, Cronin, Newton, & Gill, 2012). Akenhead and Nassis (2016) analyzed over forty responses from elite-level soccer teams across the world and the most common external training load metrics used by teams were acceleration, total high-speed distance (distance covered at speeds higher than 5.5 m/s), and estimated metabolic power (Akenhead & Nassis, 2016). Other widely used metrics not derived from GPS data that are commonly used to monitor external load combine information derived from the inertial sensors located within the units. These metrics take into consideration load from collisions and impacts (Cummins & Orr, 2015), accelerations and decelerations (Johnston, Watsford, Austin, Pine, & Spurrs, 2015; Meylan et al., 2017), and the accelerometer (Cummins & Orr, 2015). Commercial systems also use a summated load, typically calculated from the vector magnitude of accelerations, decelerations, changes of direction, and impacts in all three planes of movement (anterioposterior, mediolateral, and vertical) (Boyd, Ball, & Aughey, 2011). This is commonly referred to as PlayerLoad, measured in arbitrary units.

Training load monitoring is becoming increasingly more popular in the world of elite sports. As more teams implement monitoring systems within their organization, it is imperative that they select metrics that are valid, reliable, and will provide data that they can apply back to the preparation and performance of their club. The selection of metrics should come from previously published literature from their respective sport, or a sport with similar movement demands. A meta-analysis performed by McLaren and colleagues (2018) found that measures of internal load show positive associations with running or accelerometer-derived external loads and intensities during running-based team sports (McLaren et al., 2018). Recent findings suggest that 91% of practitioners working in high-performance sport in New Zealand and Australia implement some form of training monitoring, with a majority reporting equal focus on internal and external load monitoring (Taylor et al., 2012). Exploration of the relationship between external and internal load, or more specifically the amount of work performed, and the impact of that work performed on the athlete, provides an assessment of the individual's ability to physically respond to the session being monitored. Once the relationship between metrics is established, it can be used by practitioners to gauge individual or team fitness. More specifically, changes in internal load with respect to a standard external load may be used to infer an athletes' fitness or fatigue over time or in relation to that of their peers (Bourdon et al., 2017).

2.7 Applying Load Monitoring in Elite Sport

Several applied research papers have published how practitioners across multiple sports monitor training load with their group of athletes. While each sport offers different and unique challenges, there are specific trends regarding best practices associated with monitoring load. Above all else, the monitoring strategy needs to be valid, reliable, and repeatable, which becomes extremely important as many athletes, coaches, and team staff takes an increasingly scientific approach to load monitoring (Halson, 2014). Following the establishment of valid and reliable metrics, the monitoring system needs to be easy to use and implement from both the athlete and the practitioner. In a survey of elite rugby union teams, the most crucial factor regarding the implementation of a monitoring program was ease of use (Starling & Lambert, 2017). Athlete-compliance to a monitoring plan is crucial, especially if using self-reported methods. To help with compliance, approaches that may be the most effective at achieving high compliance with athletes include education and feedback to the athlete (Saw, Main, & Gastin, 2015). This concept is supported by Akenhead and Nassis (2016), as they found that athlete compliance on self-reported questionnaires was the number one concern regarding monitoring in elite soccer clubs, with successful clubs spending more time on player education of the data being collected (Akenhead & Nassis, 2016). Similar methods and results were supported by the work of Taylor et al. (2012) when they surveyed fifty-five high-performance practitioners across 23 sports. From this cohort, 91% of the respondents implement some form of training load monitoring, with 84% reported the use of self-reported questionnaires as one method included in their daily monitoring practice (Taylor et al., 2012). The other key requisites for an ideal monitoring protocol include non-invasive measures, non-fatiguing measures, and time-sensitive data collection (Starling & Lambert, 2017). In many instances, questionnaires were reported to have been completed on athletes' smartphones as a strategy to increase compliance. This brings the required information to a medium that the athlete is familiar with and interacts with frequently.

Sport practitioners are constantly dealing with the question of which statistics should be used versus whether statistics should be used when it comes to many facets of applying wearable data to their daily decision-making process Value lies in the certainty and priority of the critical metrics for each sport that yield the most information, provide high-value to coaches and athletes, are both valid and reliable, and can provide some predictive capability. Once these key metrics have been identified, their application could have direct implications for training and competition strategies. Even minimal changes to tactical game plans, athlete workload and performance measures may play a vital role in the outcome of matches (e.g., player deployment and tactical performance). As sporting nations continue to invest in resources for sport, the competition gap between nations appears to be decreasing (De Bosscher, De Knop, VanBottenburg, Shibli, & Bingham, 2009). Therefore, the quest to find more effective training and competition strategies is an area of focus for many elite sport teams.

After setting up a load monitoring system within a club, the practitioner must now work with the coaches and managers to ensure that there is actionable change based on the data collected. However, despite the strong evidence linking effective monitoring to enhancing numerous aspects of team performance, the main decision-makers within clubs (head coaches/managers) often perceive these strategies with skepticism (Burgess, 2017). To overcome such skepticism, it is recommended practitioners employ the following three strategies to communicate the monitoring information to the coach successfully: (1) have an appropriate understanding and analysis of the data, (2) create informative visual reports of the data, and (3) ensure appropriate communication skills to efficiently deliver this information to the coach (Buchheit, 2017). The ability to understand and communicate the collected data is where it takes on high value and is reported as simply as possible but with a high visual impact. Lastly, the communication of the information to the coach becomes valuable to provide context to the data, but also to make the data more meaningful than just numbers in a report.

More than ever, it has been observed that sport coaches, researchers, and medical practitioners have a deeper understanding of the performance demands of athletes owing to the inclusion and application of wearable technologies (Aughey, 2011). When equipped with these data, coaches may be able to make more informed decisions (Collins et al., 2015). Caution should be taken; however, when using technology to make decisions that may be perceived as exerting control over athletes (Collins et al., 2015; Jones & Denison, 2018). Although there are positive training implications from using technology, there are other potential limitations that have been assessed through a sociocultural lens (Jones & Denison, 2018; Jones, Marshall, & Denison, 2016; Manley, Palmer, & Roderick, 2012; Williams & Manley, 2016). These researchers have warned practitioners against the 'technocratic' climate of dictating athletes' performance through technology. Coaches and practitioners are encouraged to carefully consider adopting an athlete-centered approach that still promotes autonomy, identity, and motivation. When applied sensibly, technological tools have the potential to help predict, monitor, and revise coaching practices to enhance decision-making in the pursuit of performance goals (Collins et al., 2015).

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On-Ice Physical Demands of World-Class Women's Ice Hockey: From Training to Competition

Submission Type: Original Investigation

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Abstract

Purpose: To compare on-ice external and internal training loads in world-class women's ice hockey during training and competition. ***Method:*** On-ice training load were collected during one season from 25 world-class ice hockey players via wearable technology. A total of 105 on-ice sessions were recorded, which consisted of 61 training sessions and 44 matches. Paired and unpaired t-tests compared training and competition data between and across playing positions. ***Results:*** For training data, there was a difference between positions for PlayerLoad ($p < .001$, ES = 0.32), PlayerLoad·min^{-1} ($p < .001$, ES = 0.55), Explosive Efforts ($p < .001$, ES = 0.63), and TRIMP ($p < .001$, ES = 0.48). For the competition data, there were also differences between positions for PlayerLoad ($p < .001$, ES = 0.26), PlayerLoad·min^{-1} ($p < .001$, ES = 0.38), Explosive Efforts ($p < .001$, ES = 0.64), and TRIMP ($p < .001$, ES = 1.47). Similar results were found when positions were viewed independently, competition had greater load and intensity across both positions for PlayerLoad, TRIMP, and Explosive Efforts ($p < 0.001$, ES = 1.59 – 2.98); and with PlayerLoad·min^{-1} ($p = 0.016$, ES = 0.25) for the defense. ***Conclusions:*** There are clear differences in the volume and intensity of external and internal workloads between training and competition sessions. These differences were also evident when comparing the playing positions, with defense having lower outputs compared to forwards. These initial results can be used to design position-specific drills that replicate match demands for ice hockey athletes.

Keywords: Female, International, Monitoring, Technology, Team Sport, PlayerLoad

Introduction

The sport of ice hockey is characterized by athletes repeatedly performing high-intensity, short-duration efforts, while maintaining highly complex movements over the course of a 60-minute competition. For optimal performance, ice hockey athletes need to have well-rounded physical and physiological capabilities including high aerobic and anaerobic capabilities, muscular strength, power, and endurance (Ransdell & Murray, 2011). These physiological qualities are expressed in ice hockey by combining dynamic skating movement patterns with skills such as skating, shooting, and passing of the puck (Nightingale & Douglas, 2018).

The prevailing method to measure work performed on the ice in hockey research is through time-motion analysis (TMA). This involves setting up video recording equipment, monitoring players' movements, and categorizing them according to their intensity. According to the published TMA literature for female ice hockey, forwards had an average of 18 forward shifts per game, with a mean duration of 48 seconds; whilst their defensive teammates averaged 15 defensive shifts per game with an average shift duration of 43 seconds. Each shift consisted mainly of low- to moderate-intensity skating interspersed with brief, intermittent high intensity bouts; with a mean shift heart rate (HR) of 92% of player's maximum HR (Jackson & Gervais, 2016). TMA has been widely used across many team sports (Jackson & Gervais, 2016; Green, Bishop, Houston, McKillop, Norman, & Stothart, 1976; Spencer, Lawrence, Rechichi, Bishop, Dawson, & Goodman, 2004), but is often criticized when applied to sports where player movements are extremely explosive and short in duration, and therefore are difficult to record accurately (Nightingale & Douglas, 2018). Reliability of TMA is often dependent on the observer, and therefore can vary greatly based on the number of observers, expertise of the observer, and the level and sport being observed (Duthie, Pyne, & Hooper, 2003).

One potential solution to objectively quantify the movement demands in sport has been to outfit athletes with wearable technology. Due to the indoor nature of ice hockey, the use of Global Positioning System (GPS) devices is not suitable to measure the movement demands of players due to the inability to connect to satellites. Emerging research using technological advancements that incorporate triaxial accelerometry, along with the recordings of the gyroscope and magnetometer, can successfully quantify sport-specific movements (Roell, Roecker, Gerhing, Mahler, & Gollhofer, 2018). One such method to quantify the workload performed by an athlete is PlayerLoad, which sums the individual triaxial accelerometer vectors to produce an instantaneous measure of work rate, expressed in arbitrary units. PlayerLoad is calculated by using the measurements recorded via a Minimaax™ unit (Catapult Sports, Melbourne, VIC, Australia) and is defined as the "square root of the sum of the squared instantaneous rate of change in acceleration in each of the three vectors (X, Y, and Z axis) and divided by 100" (Boyd, Ball, & Aughey, 2011). PlayerLoad has been used to describe the physical and physiological demands of sports such as Australian rules football, basketball, netball, rugby, cricket, and soccer (Boyd, Ball, & Aughey, 2011; Montgomery, Pyne, & Minahan, 2010; Chandler, Pinder, Curran, & Gabbett, 2014; Hulin, Gabbett, Johnston, & Jenkins, 2018; Dalen, Jorgen, Gertjan, Havard, & Ulrik, 2016). Understanding the activity profile of a sport and quantifying the disparity between training and competition demands allows coaches and practitioners to enhance their understanding of the underlying physical and physiological load placed on the athletes. The comparison of training and competition demands can improve a coach's ability to apply a scientific framework of periodization to training programs.

To date, only one published paper has investigated the use of PlayerLoad in men's ice hockey. Van Iterson and colleagues examined the test-retest reliability of PlayerLoad during nine ice hockey tasks in a simulated game-like condition. They reported moderate-to-large test-retest reliability when using PlayerLoad to quantify on ice movements (CV 2.2-13.8%) (Van Iterson, Fitzgerald, Dietz, Snyder, & Peterson, 2017). The movement demands associated with the skating stride are inherently different than running or sprinting, as skating requires the lower limbs to move in the posterolateral plane with a large demand placed on the hip extensors, hip abductors and hip adductors. Due to the low coefficient of friction of the ice, the forward propulsion in skating needs to be perpendicular to the gliding direction of the skate, which leads to more horizontal and lateral force production than running or sprinting (Bracko, 2014).

As with the use of any technology or measuring equipment, it is imperative that the devices are valid and reliable. The Minimaax^{TM} device has been found to have an excellent intradevice reliability for PlayerLoad values, with the majority of CV values <1.0%. It has also been reported that Intraclass Correlation Coefficient (ICC) ranged from 0.8 to 1.0 for intradevice comparison (Nicolella, Torres-Ronda, Saylor, & Schelling, 2018). Along with PlayerLoad, inertial movement analysis (IMA) has been used to identify explosive actions in sports. In order for an event to register as an IMA event, there are two criteria that must be met; magnitude and direction. Inertial movement analysis data has been shown to be a valid and reliable measure to count sport-based explosive actions in female athletes (Meylan, Trewin, & McKean, 2017; Luteberget, Holme, & Spencer, 2017).

With the increased use of wearable technology to measure the work being performed in other sports, there is no research applying this technology in the sport of ice hockey. The purpose of this study is to compare the external and internal loads of world-class female ice hockey players in training and competition across the two playing positions in the sport, as well as to provide descriptive measures for coaches to make informed decisions regarding training volume and intensity in regard to match demands. The need for descriptive research is crucial for underpinning future work in the growing field of wearable technology in the sport of ice hockey (Bishop, 2008).

Methods

Subjects

Twenty-five world-class female ice hockey players were included in the analysis. All 25 athletes have represented their country in international play during the 2017-2018 season. Nine of the athletes played the defense position (age 25.0 ± 3.8 y, height 170.5 ± 4.0 cm, weight 71.1 ± 8.3 kg) and 16 played forward (age 24.7 ± 3.4 y, height 172.1 ± 4.0 cm, weight 71.1 ± 4.8 kg). This study was granted ethics exemption by the York University Office of Research Ethics on the basis that it consisted of secondary analysis of existing data and did not contain any identifying information.

Design

This study used a retrospective, secondary data analysis, with on-ice metrics for all 25 athletes collected during National Team training and competitions during the 2017-2018 season. The total number of training events for the season was 61 and the total number of competition events was 44. On average, the number of training sessions participated in for defense was 48.9 ± 11.3 and 49.3 ± 10.1 for forwards. Defensive players participated in an average of 37.1 ± 8.3 competitions during the season, and forwards participated in an average of 37.1 ± 8.3 competition sessions. Athletes would not have participated in a training session due to injury, illness, or personal leave. Athletes not participating in competition based on injury, illness, personal leave, or coach decision. During training sessions, data were recorded for the duration of each drill, and edited to exclude any non-drill-based portions of the session, which included coach-talk, drill teaching, or hydration breaks. During competitions, data were recorded for the duration of each period, and edited to exclude the time between periods.

Methodology

Athletes wore a trunk-mounted Catapult S5 unit (Catapult Sports, Melbourne, Australia; firmware version 7.27) in a monitor-specific vest worn tight against the body in compliance with the manufacturer's guidelines. The integration of 100-Hz triaxial accelerometry (quantifies linear motion in all directions – acceleration and deceleration) with triaxial 100-Hz gyroscopes (sampled at 2000° per second to measure body angular motion and rotation) and 100-Hz triaxial magnetometers (measures direction and orientation of body position) allowed for the quantification of PlayerLoad during indoor activity (Boyd, Ball, & Aughey, 2011; Van Iterson et al., 2017). The triaxial gyroscope and magnetometer functions are necessary in the aggregation of data from each specific axis in the mediolateral, vertical, and anteroposterior planes of motion to quantify PlayerLoad during dynamic multi-plane body movement (Van Iterson et al., 2017). Athletes also wore chest-strapped HR monitors (Polar H7, Polar Electro Oy, Finland), which recorded at 1-second intervals. Data from the Catapult S5 units and Polar H7 units were downloaded to a database maintained by the National Sports Organization. Catapult OpenField software (OpenField 1.17.0 Catapult Sports, Melbourne, Australia) was used for proprietary postprocessing of both the Catapult and Polar data.

The external load and intensity measures used in the analysis were:

PlayerLoad – A summation of all force across all movements, divided by 100 (Boyd, Ball, & Aughey, 2013). This was expressed as total load (arbitrary units [au]). It is calculated as:

$$\text{PlayerLoad} = \sqrt{\frac{(a_{y1} - a_{y-1})2 + (a_x - a_{x-1})2 + (a_z - a_{z-1})2}{100}}$$

Where:

a_y = Anteriorposterior accelerometer

a_x = Mediolateral accelerometer

a_z = Vertical accelerometer

PlayerLoad·minute^{-1}– an intensity metric that looks at the rate of accumulation of PlayerLoad. It was calculated by taking the PlayerLoad value and dividing it by total duration of the activity. This has been shown to be a valid measure of intensity in Australian rules football (Mooney, Cormack, O'Brien, Morgan, & McGuigan, 2013).

Explosive Efforts – a frequency count of how many explosive movements were performed. High intensity movements included: rapid accelerations and decelerations, high intensity skating, rapid changes of direction (skating-based or body contact), and high intensity shots. This count was derived from IMA data. For an event to be recorded as an explosive effort, a polynomial least squares fit was applied to the X, Y, Z resultant acceleration data and smoothed at a known frequency. This smoothed trace was overlaid with the original acceleration trace and the start and end point of the event was identified. Once identified, the sum of the X, Y area was calculated and expressed as the event magnitude (m·s^{-1}) (Innovations, 2013). Any identified movement that occurred at a rate greater than 2 m·s^{-1} in any direction was counted. The use of IMA data, outside of being able to identify explosive actions, has not been accurately quantified or validated, therefore in keeping with best practice, IMA data was selected as a count of explosive efforts.

The internal load measure used in the analysis was:

Training Impulse (TRIMP) – using Edwards TRIMP, recorded the cardiovascular demand of the session (Edwards, 1993). Edwards TRIMP uses a weighting factor that is multiplied by the time accumulated in a certain HR zone (50-59% = 1, 60-69% = 2, 70-79% = 3, 80-89% = 4, 90-100% = 5). Maximum HR values were recorded during a pre-season incremental test performed on a cycle ergometer. Values were subsequently updated if the testing values were exceeded during training or competition. TRIMP was expressed as total load (arbitrary units [au]).

Statistical Analysis

A database of identified metrics for every player in each training and competitive session was created in Excel (Microsoft Corp, Redmond, WA, USA). A normal distribution of data was confirmed via the Shapiro-Wilkes test and homogeneity of variance was confirmed with Levene's test, which allowed for the use of parametric methods of analysis. Independent sample t-tests were performed to show the difference between defense and forward during training and competition sessions. Paired-sample t-tests were performed to examine the difference between training and competition for each position. Differences between positions as well as training and competition within each position were also analyzed using effect-size (ES) statistics. Effect sizes were categorized using the following descriptors: <0.2 – trivial, 0.2-0.6 – small, >0.6-1.2 – moderate, >1.2-2.0 – large, >2.0 – very large (Hopkins, Marshall, Batterham, & Hanin, 2009). All data were processed in RStudio (version 1.0.153, R Core Team, Austria).

Results

Descriptive statistics (mean ± standard deviation) for the external and internal load and intensity measures between positions are shown in Table 3.1. Differences in external and internal load and intensity measures between and within positions are presented in Table 3.2.

Table 3.1. Mean and Standard Deviations of External and Internal Load and Intensity Categorized by Position and Session.

Position	Session	N	PlayerLoad	PlayerLoad·min^{-1}	TRIMP	Explosive Efforts
			mean ± SD	mean ± SD	mean ± SD	mean ± SD
Defense	Training	42	128.15 ± 34.29	2.09 ± 0.35	101.80 ± 41.95	162.26 ±48.21
	Competition	38	229.81 ± 34.05#	2.17 ± 0.28#	232.51 ± 75.60#	300.73 ± 60.78#
Forward	Training	42	139.96 ± 38.39*	2.28 ± 0.34*	126.01 ± 56.93*	201.37 ± 64.10*
	Competition	38	239.06 ± 36.83*#	2.28 ± 0.30*	343.64 ± 75.60*#	343.64 ± 72.64*#

Note: "*" indicates significant difference between positions (Defense and Forward)
"#" indicates significant difference between sessions (Training and Competition)

Table 3.2. Differences in External and Internal Load and Intensity Measures Between and Within Positions.

	Difference Between Forward and Defense		Difference Between Training and Competition	
	Training Effect Size (± 95% CI)	**Competition** Effect Size (± 95% CI)	**Defense** Effect Size (± 95% CI)	**Forward** Effect Size(± 95% CI)
PlayerLoad	0.32 (± 0.11)	0.26 (± 0.14)	2.98 (± 0.12)	2.63 (± 0.15)
PlayerLoad·Min^{-1}	0.55 (± 0.12)	0.38 (± 0.14)	0.25 (± 0.15)	0.0 (± 0.1)
TRIMP	0.48 (± 0.12)	1.47 (± 0.16)	2.14 (± 0.19)	1.59 (± 0.12)
Explosive Efforts	0.69 (± 0.12)	0.64 (0.14)	2.52 (± 0.20)	2.08 (±0.13)

Note: The magnitude of differences between the mean between and within positions and sessions are shown in relation to Cohen ES.

In training sessions, forwards had higher PlayerLoad ($p < .001$, ES= 0.32), PlayerLoad·min^{-1} ($p < .001$, ES = 0.55), Explosive Efforts ($p < .001$, ES = 0.63), and TRIMP ($p < .001$, ES = 0.48). During competition, forwards also had higher PlayerLoad ($p < .001$, ES = 0.26), PlayerLoad·min^{-1} ($p < .001$, ES = 0.38), Explosive Efforts ($p < .001$, ES = 0.64), and TRIMP ($p < .001$, ES = 1.47).

When positions were viewed independently, there were several differences identified between training and competition for both forwards and defense. For defensive positions, differences were evident for PlayerLoad ($p < .001$, ES = 2.98), PlayerLoad·min^{-1} ($p = .016$, ES = 0.25), Explosive Efforts ($p < .001$, ES = 2.52), and TRIMP ($p < .001$, ES = 2.14). Similar findings were found in forwards, whereby differences were found for PlayerLoad ($p < .001$, ES = 2.63), Explosive Efforts ($p < .001$, ES = 2.08), and TRIMP ($p < .001$, ES = 1.59). There was no significant difference found for forwards between training and competition for PlayerLoad·min^{-1} (p = .641, ES = 0.0). These results suggest that across measures of on-ice external and internal loads, the volume and intensity exhibited during competition is much greater than those measured during training. These differences can be seen in Figures 1 and 2.

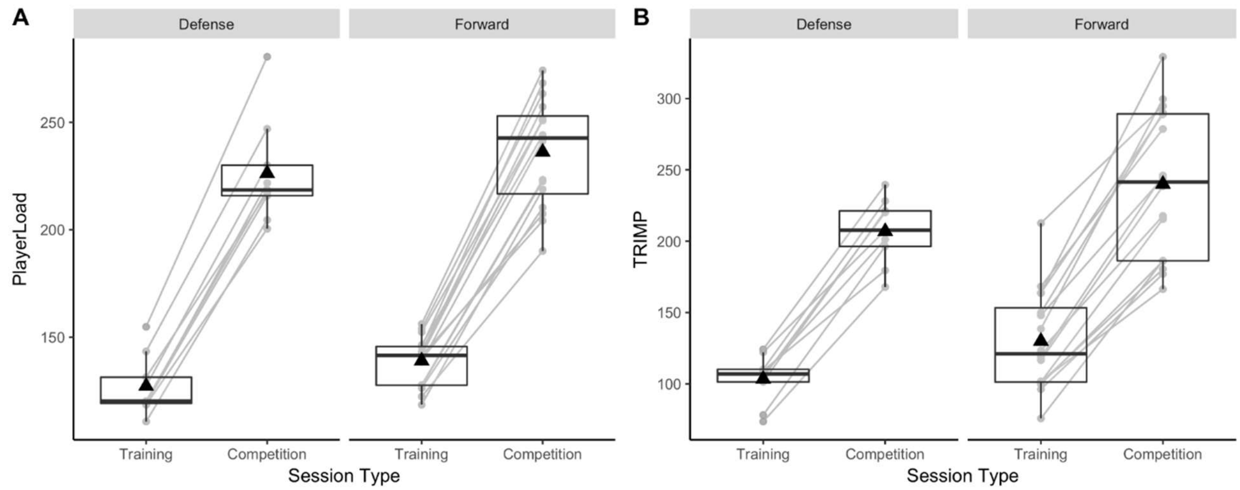

Figure 3.1 – Boxplot showing distribution and average external (A) and internal (B) load by athlete, session, and position. Grey points and lines indicate individual athlete average based off session type. "▲" denotes mean of the position and error bars represent standard deviations. " * " indicates significant difference between positions (Defense and Forward) and " # " indicates significant difference between sessions (Training and Competition).

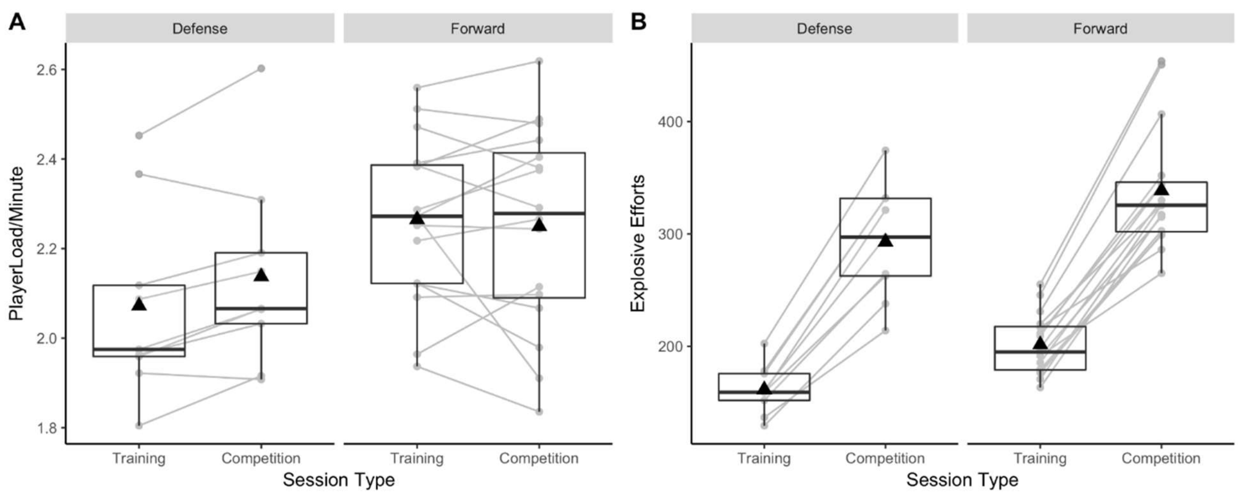

Figure 3.2 – Boxplot showing distribution and average PlayerLoad·Minute^{-1} (A) and Explosive Effort count (B) by athlete, session, and position. Grey points and lines indicate individual athlete average based off session type. "▲" denotes mean of the position and error bars represent standard deviations. " * " indicates significant difference between positions (Defense and Forward) and " # " indicates significant difference between sessions (Training and Competition).

Discussion

To the authors' knowledge, this study is the first to quantify on-ice movements in world-class ice hockey using accelerometers. The first major finding from this investigation was that there are differences in both external and internal load measures between training and competition for the playing positions. Forwards had both higher volumes and intensities of load measures than defense in both training and competition. These findings are consistent with TMA-based observations, which found that defensive players had greater amounts of time in stationary positions than forwards and skated at a lower intensity for longer periods of time during competition (Jackson & Gervais, 2016). The higher PlayerLoad and PlayerLoad·min^{-1} values for forwards could be attributed to the fact that forwards have a higher mean skating velocity compared to defense and forwards tend to skate at a higher intensity for a longer duration (Jackson & Gervais, 2016; Dillman, Stockholm, & Greer, 1984). This difference could be due to tactics of play, as many teams employ an aggressive forecheck-style, which requires the forwards to skate harder at their opponent and increase the pace of play in all three zones of the ice. In this study, forwards had a greater number of explosive efforts in both training and competition, which could be attributed to style and positional pace of play. As most of the previous work regarding workload during training and games has been derived from TMA, this study has provided objective measures of on-ice work.

Similar to the results regarding external load measures, forwards exhibited higher levels of internal load. Previous literature on HR-derived information in ice hockey is mixed. Some studies have found that there is no difference between forwards and defense when measuring mean HR (Jackson & Gervais, 2016; Green et al., 1976). Conversely, in female ice hockey players, Spiering and colleagues found that competition HRs were much higher than those measured in training, however they also reported no difference in average or peak HR between positions (Spiering, Wilson, Judelson, & Rundell, 2003). This is supported by more recent work with semi-elite female ice hockey players that found that there was no difference in peak or mean HR between forwards and defense (Jackson & Gervais, 2016). It should be noted that previous literature has focused on mean and peak HR values instead of a cumulative load measure such as TRIMP. The current study chose to measure TRIMP as it has been shown to be a reliable measure of both intensity and internal training load in previously published work with team-based load monitoring (Alexiou & Coutts, 2008; Scanlan, Wen, Tucker, & Dalbo, 2014; Stagno, Thatcher, & Van Someren, 2007).

In both positions, data for external and internal loads were different based on the type of session. In all cases, training session loads and intensities were lower than competition sessions. The higher competition loads could be attributed to the more competitive and physical nature of match-play, along with the higher pace associated with competition. The amount and duration of coaching at training could account for the lower intensity and workload of these sessions. Periods of instruction and skill work, with a focus on technical and tactical improvement are often prevalent in training sessions, which would have a lower intensity than competitive periods of play. It is suggested that coaches aiming to replicate competition demands include competitive-based drills or small-sided games during training sessions (Boyd, Ball, & Aughey, 2013).

The measuring of positional characteristics in training and competition, while novel in ice hockey, is well-established in other sports. For example, similar differences between positions in regard to external load has been shown in Australian Football, where PlayerLoad varied across the different positions (Boyd, Ball, & Aughey, 2013). Comparable findings regarding the disparity between training and competition loads have been reported in international rugby sevens as well. Relative to competition, training data were shown to be lower in intensity (maximal velocities, impacts, accelerations and decelerations, mean HR, peak HR, and TRIMP) and volume (total distance covered) (Higham, Pyne, Anson, Hopkins, & Eddy, 2016). Gabbett replicated the examination in elite female field hockey players with similar results, concluding that athletes had decreased volumes and intensities in training compared to competition and that training sessions were a poor reflection of the physiological demands of competition (Gabbett, 2010).

The current study is novel in terms of the sport (ice hockey), participant group/gender (world-class female players), and technology used (accelerometers), however it also has some limitations. Direct comparisons with previously published accelerometer-derived data were not possible due to the paucity of literature in high-level female ice hockey players. Athletes wore the same unit every session, while consistent, can introduce bias as accelerometers have been found to show poor interunit reliability (Nicolella et al., 2018). Another limitation is that there was no correction for the natural fluctuation of volume and intensity based off weekly schedules. All the training sessions were included in the data set, without identifying high load or low load days. Further research can investigate the periodization of planning that occurs during an ice hockey season. Future work investigating internal load using TRIMP should focus on using a modified TRIMP, which has been shown to provide a measure of internal load during team sports of a high-intensity and intermittent nature. The use of modified TRIMP in intermittent, high intensity sport has merit as it applies a different weighting factor for each HR zone that resembles a typical blood lactate response curve, thus the duration of work performed at higher HR zones can be exponentially weighted (Stagno, Thatcher, & Van Someren, 2007). The inclusion of high-level athletes, while a unique data set, might limit the generalizability to other populations. There is a paucity of research in the application of wearable technology to monitor both external and internal load in ice hockey, as the body of research grows it will be important to begin to understand the unique movement patterns and movements strategies that are inherent to ice hockey, such as the impact of low-intensity locomotion or gliding and its relationship to external and internal loads. As this is the only investigation to date assessing accelerometers in ice hockey training and competition, further investigation is required to develop a greater understanding of the role these devices can play in improving player performance.

Practical Application

The results of the present study demonstrate that wearable technology, in the form of accelerometers and HR monitors, provide valuable information regarding the on-ice volumes and intensities of both training and competition in ice hockey. This information can be used by coaches to further improve their training sessions and closely mirror competition demands. The information collected from wearable technology quantifies athletic performance and allows coaches to make informed decisions. Coaches could benefit from spending time working the positions separately and use the information contained within to better prepare athletes for the demands of competition. This information can be used to prescribe position-specific training approaches to further enhance the training process. Furthermore, the differences between positions are important as coaches need to plan training that reflects adequate work volume and intensity for both positions to help mitigate undertraining in relation to competitive demands.

Conclusion

Specificity of training is an important consideration for the prescription of physical performance programs to elicit physiological adaptations to improve competitive performance.

Understanding the differences between positions, as well as training and competition demands can further refine the athlete preparation process. The use of wearable technology in elite sports is growing, as such ice hockey is a sport to which the information collected from these units can provide objective data regarding the on-ice demands. There are clear differences in the volume and intensity of external and internal workloads between training and competition sessions, with athletes experiencing much less across all measures in training sessions. Understanding the demands of competition facilitates the modification of training drills to improve specificity and adopt position-specific training approaches. Similarly, these differences were also evident when comparing the skating positions, with defense having lower loads and intensities compared to forwards. We conclude that there are markedly different volume and intensity outputs between training and competition, and this information will allow coaches and athletes to design improved training sessions to increase their complexity and intensity to better simulate the demands of competition. Monitoring the external and internal competition loads provides coaches a quantified approach to ensure that training demands are high enough to optimally prepare players for the demands of competition.

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CHAPTER 4: MANUSCRIPT TWO

Submitted for review to the Journal of Strength and Conditioning Research. Included here in the format required for submission to the journal.

A Comparison of On-Ice External Load Measures Between Sub-Elite and Elite Female Ice Hockey Players

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Abstract

This study quantified and examined differences in measures of on-ice external load for sub-elite and elite female ice hockey players. External load variables were collected from sub-elite (N = 21) and elite (N = 24) athletes using Catapult S5 monitors during the pre-season. A total of 574 data files were analyzed from training and competition during the training camp. Significant differences between groups were found across all variables. Differences in training between the two groups ranged from trivial (forwards PlayerLoad, $p = 0.03$, ES = 0.18) to large (forwards Explosive Efforts, $p < 0.001$, ES = 1.64; defense Explosive Efforts, $p < 0.001$, ES = 1.40). Match comparisons yielded similar results, with differences ranging from small (defense Low Skating Load, $p = 0.05$, ES = 0.49; Medium Skating Load, $p = 0.04$, ES = 0.52; High Skating Load, $p = 0.02$, ES = 0.63) to very large (forwards PlayerLoad, $p < 0.001$. ES = 2.25; PlayerLoad·min^{-1}, $p < 0.001$, ES = 2.17; Explosive Efforts, $p < 0.001$, ES = 2.03; Medium Skating Load, $p < 0.001$, ES = 2.31), respectively. The differences in external load measures of intensity demonstrate the need to alter training programs of sub-elite ice athletes to ensure they can meet the demands of elite ice hockey. As athletes advance along the development pathway, considerable focus of their off-ice training should be to improve qualities that enhance their ability to perform high-intensity on-ice movements.

Key Words: Wearable, Technology, GPS, Accelerometer, Team Sport

Introduction

Research on international female ice hockey has provided both a descriptive analysis of the differing movement demands between positions, as well as the differences during training and within the actual game (Douglas, Johnston, et al., 2019; Douglas, Rotondi, Baker, Jamnik, & Macpherson, 2019). Previous work has also explored the physical and physiological systems needed to perform at the highest levels of women's hockey (Ransdell & Murray, 2011). This information has been beneficial for practitioners and coaches in the sport as it provides valuable information about the match demands, which coaches can use to ensure their training sessions mirror the intensity demands recorded during matches. Similarly, coaches can use this information to prescribe position-specific training approaches to enhance the training process further. In contrast, limited research has been conducted examining the external load movement demands of players involved in sub-elite female ice hockey. This information is crucial as it has implications for the movement of players between different tiers of competition (regional to international-level) (Bishop, 2008). Evidence from other team sports suggests this information could assist with identifying development requirements for players to meet the demands of competition at the highest level of their sport (Sirotic, Coutts, Knowles, & Catterick, 2009). As international sporting federations continue to invest in resources for sport, the competition gap between nations appears to be decreasing (De Bosscher, De Knop, VanBottenburg, Shibli, & Bingham, 2009). Therefore, the quest to find more effective training and competition strategies is an area of focus for many elite sport teams.

The use of wearable technology has been widespread in many outdoor sports as units typically include a global positioning system (GPS) unit, accelerometer, gyrometer, and magnetometer. Wearable technologies are appealing to athletes due to their non-invasive ability to collect data, as they are small, lightweight, and worn close to the skin (Halson, Peake, & Sullivan, 2016). In field-based sports, wearable technologies have been used to objectively measure movement demands, assess the differences between practice and competition demands, and provide information regarding high-intensity movements (Dellaserra, Gao, & Ransdell, 2014). With the increased availability of wearable technologies, including accelerometers and ultra-wideband positioning systems for indoor sports, there is a need to better understand the movement-related outputs within sports such as ice hockey at all levels of competition.

To date, there are few studies that have examined on-ice data via wearable technology worn during training and competition in female ice hockey players (Douglas, Johnston, et al., 2019; Douglas, Rotondi, et al., 2019). This information can provide practitioners with valid, reliable, and practical methods to quantify the external load players encounter in matches. As technology has become smaller and more reasonably priced, it could also play a role in talent identification. It is not uncommon for national sporting bodies, federations, and team administrators to seek methods that may enhance the efficiency of athlete skill development (Abernethy, 2007). If specific variables can be identified that are associated with aspects of performance in a given sport, potential talent might be identified early in development and training programs could be designed to more effectively develop these attributes ultimately improving performance of athletes in the sport (Geithner, 2009). The development of technical game-play differences between elite and sub-elite developmental athletes has been identified as a potential key performance indicator to track as athletes progress in their sport that might have relevance for talent identification (Woods, Bruce, Veale, & Robertson, 2016). This game-play evidence can be easily collected via athlete-worn microtechnology units that measure GPS and accelerometer-based metrics that accurately measure athlete workloads in team sports (Fenner, Iga, & Unnithan, 2016; Goto, Morris, & Nevill, 2015; Woods et al., 2016).

Previous work comparing elite to sub-elite female ice hockey players has focused on performance-based metrics outside of on-ice training or match comparison. On-ice physical testing has revealed that elite players tended to be older and faster, with higher levels of aerobic and anaerobic performance on skating tests (Bracko, 2001). The better performance of elite players has been attributed to the specialized training that higher-level athletes perform on a consistent basis. It has also been found that female ice hockey players from countries that have more success in international competition have higher levels of lower body power than their less successful counterparts (Ransdell, Murray, & Gao, 2013). However, there is no information on what makes these athletes successful aside from their physical profile as there is no information regarding the on-ice movement demands of sub-elite ice hockey players measured during the completion of their sporting activity.

Therefore, the aims of this study were (a) to describe the movement demands of the sub-elite female ice hockey players in training and competition and (b) to examine whether differences exist in the movement demands between elite and sub-elite female ice hockey players. We hypothesized that players competing at the highest level would perform more higher-intensity movements and work at a higher intensity than sub-elite players.

Methods

Experimental Approach to the Problem

This study consisted of athletes who represent their country at the international level and athletes who compete at the collegiate ice hockey level. This work builds off previous literature that investigated the movement demands of world-class female ice hockey athletes by providing information regarding a sub-population of female ice hockey (Douglas, Rotondi, et al., 2019). The movement variables analyzed were selected based on previous studies investigating the use of wearable technology in team sports as well as those identified by the coaching and sport science staff (Douglas, Johnston, et al., 2019; Douglas, Rotondi, et al., 2019; Meylan, Trewin, & McKean, 2017).

From a grassroots level, female hockey has seen tremendous growth over the last twenty-five years. Participation in women's hockey in North America has grown over 900%, from approximately 6,000 in 1990 to 75,832 in 2017 in the USA (USA Hockey, 2017) and from 8,146 in 1990 to 88,541 in 2017 in Canada (Hockey Canada, 2017). This study used a retrospective, secondary data analysis, with on-ice metrics for all 45 athletes collected during a preseason training camp.

Subjects

Twenty-four elite and 21 sub-elite female ice hockey players were included in the analysis. The total number of on-ice events included in the analysis was 29, with nine training sessions and five matches for the elite group and ten training sessions and five matches for the sub-elite group.

All 24 elite athletes represented their country in international play during the 2016-2017 season. Nine of the athletes played the defense position (age 25.0 ± 3.8 y, height 170.5 ± 4.0 cm, body mass 71.1 ± 8.3 kg) and 15 played forward (age 23.4 ± 3.2 y, height 173.4 ± 4.5 cm, body mass 70.2 ± 4.7 kg). The sub-elite group consisted of players from collegiate ice hockey, where eight played the defense position (age 20.3 ± 1.1 y, height 167.9 ± 4.8 cm, body mass 66.8 ± 4.2 kg) and 13 played forward (age 20.5 ± 1.1 y, height 167.1 ± 5.1 cm, body mass 62.2 ± 6.3 kg). Written informed consent was obtained by the National Sports Organization from the players before the study, and the study conformed to the code of ethics of the Declaration of Helsinki. This study was granted ethics exemption by the York University Office of Research Ethics on the basis that it consisted of secondary analysis of existing data and did not contain any identifying information.

Procedures

Data were collected over a three-week training camp during the preseason portion of the competitive calendar. Two hundred seventy total files were collected for the elite athletes (182 training and 88 match files), and 304 total files were collected for the sub-elite athletes (204 training and 100 match files). Athletes at their respective level wore a trunk-mounted Catapult S5 unit (Catapult Sports, Melbourne, Australia; firmware version 7.27) in a monitor-specific vest worn tight against the body in compliance with the manufacturer's guidelines. The integration of 100-Hz triaxial accelerometry (quantifies linear motion in all directions – acceleration and deceleration) with triaxial 100-Hz gyroscopes (sampled at 2000° per second to measure body angular motion and rotation) and 100-Hz triaxial magnetometers (measures direction and orientation of body position) allowed for the quantification of Player Load (PL) during indoor activity (Boyd, Ball, & Aughey, 2011; Van Iterson, Fitzgerald, Dietz, Snyder, & Peterson, 2017). Athletes wore the same unit for each session to control for inter-unit reliability, as recommended in previous studies (Nicolella, Torres-Ronda, Saylor, & Schelling, 2018; Van Iterson et al., 2017).

The movement demands examined were based on research in ice hockey and other team sports of similar movement demands (Douglas, Rotondi, et al., 2019; Van Iterson et al., 2017; Wik, Luteberget, & Spencer, 2017). Specifically, these movement demands included: (a) PL (Douglas, Rotondi, et al., 2019; Van Iterson et al., 2017), (b) PlayerLoad$\cdot$min^{-1} (PL$\cdot$min^{-1})

(Douglas, Rotondi, et al., 2019; Luteberget & Spencer, 2017; Mooney, Mitchell, Cormack, O'brien, Morgan, & McGuigan, 2013), (c) Explosive Efforts (EE) (Douglas, Rotondi, et al., 2019; Meylan et al., 2017), (d) Explosive Efforts$\cdot$min^{-1} (EE$\cdot$min^{-1}) and (e) skating load at low (< 100 a.u.), medium (101-139 a.u.) and high (>140 a.u.) intensities (Douglas, Johnston, et al., 2019). Due to the variable duration of training and competition because of player deployment and session length, PL and EE were also expressed as a per-minute variable similar to previously published athlete monitoring data (Johnston, Watsford, Austin, Pine, & Spurrs, 2015; Johnston et al., 2012; Sirotic et al., 2009)

Following each session, data from the Catapult S5 units were downloaded to a database maintained by the National Sports Organization. Catapult OpenField software (OpenField 1.17.0 Catapult Sports, Melbourne, Australia) was used for proprietary postprocessing of the data. During training sessions, data were recorded for the duration of each drill and edited to exclude any non-drill-based portions of the session, which included coach-talk, drill teaching, or hydration breaks. During competitions, data were recorded for the duration of each period and edited to exclude the time between periods. This is consistent with best practices from other studies that have examined training and competition demands of team sports (Coutts, Quinn, Hocking, Castagna, & Rampinini, 2010; Douglas, Rotondi, et al., 2019; Gabbett, Jenkins, & Abernethy, 2012; Johnston et al., 2012).

It has been previously determined that Catapult S5 units can be used confidently for analysis for indoor team sports, with Coefficient of Variation (CV) values reported as <1.0% (Nicolella et al., 2018). It has also been reported that the Intraclass Correlation Coefficient (ICC) ranged from 0.8 to 1.0 for intradevice comparison (Nicolella et al., 2018). Along with PL, inertial movement analysis (IMA) has been used to identify explosive actions in sports. Inertial movement analysis data have been shown to be a valid and reliable measure to count sport-based explosive actions in female athletes (Luteberget, Holme, & Spencer, 2017; Meylan et al., 2017).

Statistical Analyses

All data were processed in RStudio (version 1.0.153, R Core Team, Vienna, Austria). Descriptive statistics for all variables were calculated and reported as mean ± SD. Positional groups were compared separately due to the differences in on-ice demands associated with each position (Douglas, Rotondi, et al., 2019). Each set of data was tested for normality using the Shapiro-Wilk's test. For data that were not normally distributed, an unpaired two-sample Wilcoxon test was performed. All other data were analyzed using independent samples t-tests to show the difference between elite and sub-elite athletes during training and competition sessions. A significance level of $p \leq 0.05$ was set as the level of significance for all tests. Differences between the two levels were also analyzed using Cohen's D for effect-size (ES) statistics. Effect Sizes were categorized using the following descriptors: <0.2 – trivial, 02.-0.6 – small, >0.6-1.2 – moderate, >1.2-2.0 – large, >2.0 – very large (Hopkins, Marshall, Batterham, & Hanin, 2009).

Results

Elite players from both positions showed significant differences across most of the movement demand variables compared to their sub-elite counterparts (Tables 4.1 and 4.2). For forwards (Table 4.1), a trivial difference was found for PL (4.1%), a moderate difference for PL·min^{-1} (23.5%), a large difference in EE (91%), and a moderate difference in EE·min^{-1} (31.9%). For the skating load variables, a small difference was found for low skating load (19.8%) and medium skating load (24.0%), whereas a large difference was found for high skating load (131.4%). For defensive players (Table 4.2), a small difference was found for PL (13.7%) and a large difference in EE (87.9%). For skating load variables, significant differences ranged from moderate for low skating load (63.3%) to small for medium (5.8%) and high skating load (91%).

Table 4.1. On-Ice External Load demands during training for Sub-Elite (Collegiate level) and Elite (National Team) female ice hockey forwards.

Select External Load Variables	**Sub-elite N = 126**	**Elite N = 113**	**Difference (%)**	**Mean Difference (95% Confidence Interval)**	***P***	**Effect Size (ES)**
PlayerLoad	158.8 ± 40.5*	152.3 ± 31.0	-4.1	- 6.5 (0.66 to 17.45)	0.03	0.18
PlayerLoad·min^{-1}	1.7 ± 0.5*	2.1 ± 0.3	23.5	0.4 (-0.40 to -0.25)	< 0.001	0.99
Explosive Efforts	473.0 ± 327.2*	903.3 ±164.0	91.0	430.3 (-582.00 to -443.00)	< 0.001	1.64
Explosive Efforts·min^{-1}	2.2 ± 0.8*	2.9 ± 0.6	31.8	0.7 (-0.80 to -0.48)	< 0.001	1.00
Skating Load						
Low Skating	600.4 ± 220.7*	481.4 ± 109.0	-19.8	- 119 (71.23 to 164.15)	< 0.001	0.68
Medium Skating	330.5 ± 159.4*	409.7 ± 104.3	24.0	79.2 (-113.81 to -44.60)	< 0.001	0.58
High Skating	105.5 ± 162.7*	244.1 ± 153.1	131.4	138.6 (-178.96 to -101.10)	< 0.001	0.88

*Significantly different from elite group, $p \leq 0.05$. PlayerLoad and Skating Load are displayed in arbitrary units (a.u.).

Table 4.2. On-Ice External Load demands during training for Sub-Elite (Collegiate level) and Elite (National Team) female ice hockey defensive players.

Select External Load Variables	Sub-elite N = 78	Elite N = 69	Difference (%)	Mean Difference (95% Confidence Interval)	*P*	Effect Size (ES)
PlayerLoad	157.5 ± 43.0*	135.9 ± 26.4	-13.7	-21.6 (12.41 to 32.67)	< 0.001	0.59
PlayerLoad·min^{-1}	1.6 ± 0.6	1.8 ± 0.3	12.5	0.2 (-0.22 to 0.01)	0.06	0.45
Explosive Efforts	435.8 ± 351.0*	818.8 ± 148.2	87.9	383 (-571.00 to -413.00)	< 0.001	1.40
Explosive Efforts·min^{-1}	2.0 ± 0.8*	2.3 ± 0.6	15	0.3 (-0.47 to - 0.01)	0.04	0.49
Skating Load						
Low Skating	588.6 ± 215.9*	475.0 ± 130.0	-63.3	-372.7 (44.74 to 159.58)	< 0.001	0.63
Medium Skating	288.3 ± 151.4	305.1 ± 107.8	5.8	16.8 (-60.45 to 26.87)	0.45	0.13
High Skating	71.6 ± 53.1*	136.7 ± 143.7	91.0	65.1 (-43.25 to -7.28)	0.01	0.60

*Significantly different from elite group, $p \leq 0.05$. PlayerLoad and Skating Load are displayed in arbitrary units (a.u.).

Significant differences were evident between the two groups for all variables during competition (Tables 4.3 and 4.4). With the forward position (Table 4.3), very large differences were found for PL (54.0%), PL·min^{-1} (53.3%), and EE (66.1%), with large differences for EE·min^{-1} (63.2%). Effect sizes for skating load variables were found to be moderate for low skating load (24.2%), very large for medium skating load (113.7%), and large for high skating load (402.0%). Competition demands for defense players (Table 4.4) showed moderate effect sizes for PL (24.3%), PL·min^{-1} (22.2%), EE (30.7%), and EE·min^{-1} (33.3%) and small differences for low (19.4%), medium (19.7%), and high skating loads (104.5%).

Table 4.3. On-Ice External Load demands during competition for Sub-Elite (Collegiate level) and Elite (National Team) female ice hockey forwards.

Select External Load Variables	**Sub-elite N = 62**	**Elite N = 57**	**Difference (%)**	**Mean Difference (95% Confidence Interval)**	***P***	**Effect Size (ES)**
PlayerLoad	159.5 ± 39.0*	245.6 ± 37.4	54.0	86.1 (-99.94 to -72.19)	< 0.001	2.25
PlayerLoad·min^{-1}	1.5 ± 0.3*	2.3 ± 0.3	53.3	0.8 (-0.86 to -0.62)	< 0.001	2.17
Explosive Efforts	819.2 ± 293.7*	1361 ± 234.5	66.1	541.8 (-657.00 to -458.00)	< 0.001	2.03
Explosive Efforts·min^{-1}	1.9 ± 0.7*	3.1 ± 0.6	63.2	1.2 (-1.49 to -1.01)	< 0.001	1.88
Skating Load						
Low Skating	550.7 ± 208.9*	684.2 ± 172.7	24.2	133.5 (-202.90 to -64.14)	< 0.001	0.69
Medium Skating	299.9 ± 156.1*	640.9 ± 137.5	113.7	341 (-413.20 to -311.33)	< 0.001	2.31
High Skating	88.2 ± 92.4*	442.8 ± 260.1	402.0	354.6 (-368.10 to -235.63)	< 0.001	1.85

*Significantly different from elite group, $p \leq 0.05$. PlayerLoad and Skating load are displayed in arbitrary units (a.u.).

Table 4.4. On-Ice External Load demands during competition for Sub-Elite (Collegiate level) and Elite (National Team) female ice hockey defensive players.

Select External Load Variables	Sub-elite N = 38	Elite N = 31	Difference (%)	Mean Difference (95% Confidence Interval)	*P*	Effect Size (ES)
PlayerLoad	183.0 ± 44.3*	227.5 ± 56.4	26.4	47.5 (-69.37 to -19.64)	< 0.001	0.89
PlayerLoad·min^{-1}	1.8 ± 0.4*	2.2 ± 0.3	22.2	0.4 (-0.54 to -0.19)	< 0.001	0.99
Explosive Efforts	1051.8 ± 385.5*	1374.0 ± 341.5	30.6	322.2 (-603.00 to -133.00)	0.002	0.88
Explosive Efforts·min^{-1}	2.1 ± 0.8*	2.8 ± 0.7	33.3	0.7 (-1.21 to -0.41)	< 0.001	1.00
Skating Load						
Low Skating	672.7 ± 246.5*	803.1 ± 287.2	19.4	130.4 (-260.90 to 0.26)	0.05	0.49
Medium Skating	422.2 ± 141.7*	505.2 ± 177.5	19.7	83 (-161.72 to -4.30)	0.04	0.52
High Skating	113.3 ± 60.9*	231.7 ± 270.6	104.5	118.4 (-69.56 to -11.68)	0.02	0.63

*Significantly different from elite group, $p \leq 0.05$. PlayerLoad and Skating load are displayed in arbitrary units (a.u.).

Discussion

This study compared the differences between sub-elite and elite training and competition data collected via wearable technology in female ice hockey. The data indicated clear differences in the actions performed at high intensity between the two groups. Elite athletes completed a higher number of movements at high intensity, both as an absolute and a per-minute basis. These findings, along with the other external load demands investigated, highlight a clear difference between elite and sub-elite players. Similar differences between skill groups in regards to high-intensity external load metrics have also been found in other team sports such as Australian football (Johnston et al., 2015), soccer (Mohr, Krustrup, & Bangsbo, 2003), and rugby (Sirotic et al., 2009). Additionally, the results of this study provide a useful descriptive analysis of the on-ice movement demands of sub-elite female ice hockey players. This research can inform sport coaches, conditioning coaches, and players along their development pathway if they choose to extend their career from the sub-elite to elite level.

Our results also demonstrate that intensity-based outputs, such as EE and high skating load, were significantly higher for both positions in the elite group, with greater ES for the forward positions in the elite players. With both positions, the results indicate that elite athletes have higher competitive workloads and intensities than the sub-elite athletes. Previous work with elite female ice hockey players has shown that competition demands are higher than training demands, especially for forwards (Douglas, Rotondi, et al., 2019). It can be reasoned that match demands associated with tactics of play, including an aggressive forecheck-style, require the higher intensity output for forwards. One such reason for this could be that forwards typically have a higher mean skating velocity and tend to skate for a longer duration during a match (Jackson & Gervais, 2016; Lignell, Fransson, Krustrup, & Mohr, 2018).

It is possible that the elite ice hockey players are more skilled, and thus are more efficient at producing high-intensity skating movements than their sub-elite counterparts. Inefficient skating mechanics could explain the higher PL values of the sub-elite athletes in practice. The calculation of PL takes into account anteroposterior acceleration, mediolateral acceleration, and vertical acceleration, as such the difference could be attributed to extraneous body movement during skating for the sub-elite athlete group. Elite ice hockey players have been found to skate with more forward flexion of their trunk during both the hockey stride and glide, whereby less skilled skaters tend to have a more upright posture (Bracko, 2004). To propel forward, the angle of the skating push occurs perpendicular to the gliding direction of the skate, which results in abduction and adduction movements of the legs (Bracko, 2004). This unique skating movement, along with a more upright trunk, could result in higher mediolateral and vertical accelerometer values, and in turn result in a higher recorded PL during controlled drills in training. Previous literature in running-based tasks has found that athletes who keep a more vertical trunk when running and sprinting have higher PL values due to the increased contribution of the vertical acceleration and the differences in locomotive skills associated with the task (Barreira et al., 2017).

Skating is a skill, and differences have been previously found when comparing high caliber and low caliber ice hockey athletes. Using on-ice motion capture, it has been shown that higher caliber male ice hockey players had greater forward velocities and accelerations due to faster joint speed and greater vertical center of mass; which allowed the elite athlete to hold positions of acceleration for longer durations, while also being able to align their skates to allow for a more powerful stride quicker than lower caliber skaters (Renaud et al., 2017). Elite skaters also have a greater stride length, which allows them to produce power for a longer duration through their stride, maximizing their strength potential (Upjohn, Turcotte, Pearsall, & Loh, 2008). Along with stride length, elite skaters show a higher stride frequency, thus allowing them to increase both the force per stride and number of opportunities to produce force (Marino, 1977; Wu, Pearsall, Russell, & Imanaka, 2016). Taken together, elite athletes possess the skill required to put their skates in the optimal position to maximize their strength and power.

A key component of high-intensity work is having the requisite strength required to produce the power needed to move fast. The on-ice results of this study, where elite athletes had higher outputs are consistent with off-ice physical measures. Elite ice hockey players have shown higher indicators of lower body strength and power compared to their sub-elite peers, such as higher and further jumping during traditional off-ice jumping tests (Upjohn et al., 2008). Off-ice speed and power testing has consistently shown a strong relationship to on-ice skating speed, with faster skaters exhibiting higher scores in muscular power tests such as the vertical jump (Bracko & Fellingham, 1997; Bracko & George, 2001; Diakoumis & Bracko, 1998; Farlinger, Kruisselbrink, & Fowles, 2007; Mascaro, Seaver, & Swanson, 1992) Specifically with female athletes, faster skaters on the ice had higher scores in both the vertical and broad jump, faster sprint times, and higher power outputs (Watts and Watts/kg) as measured by a traditional Wingate test (7.5% of body mass) (Janot, Beltz, & Dalleck, 2015).

Practical Application

This study reported descriptive data of on-ice external load demands for elite and sub-elite female ice hockey players. It was evident that elite players performed significantly more explosive efforts and had higher intensity-based measures of external loads than sub-elite athletes during training and competition. As athletes progress along the development pathway, considerable focus of their training should be directed to improving qualities that can enhance their ability to perform high-intensity movements on the ice. Specifically, strength and conditioning coaches working with women's ice hockey teams should focus on increasing lower body strength and power using a multitude of strategies and modalities based on the age of the developing athlete and their movement competency. The findings are also beneficial because the use of wearable technology at all levels is increasing, and the data of both elite and sub-elite female athletes can be used by players and coaches as a tool for evaluating effective program design and goal setting, both on and off the ice. Strength and conditioning professionals currently struggle to find data on elite female athlete populations to use for goal setting, motivation, and comparison purposes, and the need for sport and position profiling is well documented (Ransdell et al., 2013). We conclude that there are markedly different PlayerLoad (volume) and intensity outputs between levels of female ice hockey players in both training and competition, and this information will allow coaches and athletes to design improved training sessions to better prepare their athletes along the development pathway.

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CHAPTER FIVE: MANUSCRIPT THREE

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On-Ice Measures of External Load in Relation to Match Outcome in Elite Female Ice Hockey

Submission Type: Article

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Abstract: The aim of this study is to investigate the differences between select on-ice measures using inertial movement sensors based on match outcome, and to determine changes in player movements across three periods of play. Data were collected during one season of competition in elite female ice hockey players (N = 20). Two-factor mixed effects ANOVAs for each skating position were performed to investigate the differences in match outcome, as well as differences in external load measures during the course of a match. For match outcome, there was a small difference for forwards in explosive ratio (p = 0.02, ES = 0.26) and percentage high force strides (p = 0.04, ES = 0.50). When viewed across three periods of a match, moderate differences were found in skating load (p = 0.01, ES = 0.75), explosive efforts (p = 0.04, ES = 0.63), and explosive ratio (p = 0.002, ES = 0.87) for forwards, and in PlayerLoad (p = 0.01, ES = 0.70), explosive efforts (p = 0.04, ES = 0.63), and explosive ratio (p = 0.01, ES = 0.70) for defense. When examining the relevance to match outcome, external load measures associated with intensity appear to be an important factor among forwards. These results may be helpful for coaches and sport scientists when making decisions pertaining to training and competition strategies.

Keywords: monitoring; PlayerLoad; skating load; explosive efforts; explosive ratio; percentage of high force strides

Introduction

Ice hockey is a major international sport with over one million registered participants across the globe (Nightingale & Douglas, 2018). For optimal performance, ice hockey athletes require well-rounded physical and physiological capabilities (amongst other qualities), including high aerobic and anaerobic capabilities, muscular strength, power, and endurance (Ransdell & Murray, 2011). These physiological qualities are expressed in ice hockey by combining dynamic skating movement patterns with skills such as skating, shooting, and passing of the puck (Nightingale & Douglas, 2018).

The incorporation of evidence-based approaches into training has become a critical component in many competitive sports, including ice hockey. This movement is reflected in the integration of sport science experts (analysts, medical teams, and researchers), as well as in an increased use of technology to help increase scientific rigor (Balagué, Torrents, Hristovski, & Kelso, 2017; Paul & Ellapen, 2016). Specifically, the inclusion of wearable technologies (also known as 'wearables'), such as heart rate monitors, global positioning systems (GPS), and accelerometers, has become common in many elite sport programs. In 2016, wearables (both consumer-based and athlete-based) were estimated to be a six-billion-dollar industry (Düking, Hotho, Holmberg, Fuss, & Sperlich, 2016). It is believed that the use of wearables may enhance coaches' decision-making practices, while also helping to optimize player performance (Collins, Carson, & Cruikshank, 2015). Specifically, training interventions, tactical assessments, competition preparation, and athlete feedback are just some of the areas influenced by the incorporation of wearable technologies in sport programs (Carling, Wright, Nelson, & Bradley, 2014; Jones & Denison, 2018; Mackenzie & Cushion, 2013). It is the hope that collecting and analyzing data from wearables, along with appropriately interpreting and applying the findings, can improve consistency of performance outcomes and the prevention of excess fatigue and overuse injuries (Burgess, 2017). The prevailing method to measure work performed on the ice in hockey research is through time-motion analysis (TMA). TMA has been widely used across many team sports (Green, Bishop, Houston, McKillop, Norman, & Stothart, 1976; Jackson & Gervais, 2016; Spencer, Lawrence, Rechichi, Bishop, Dawson, & Goodman, 2004), but is often criticized when applied to sports where player movements are extremely explosive and short in duration, and therefore difficult to record accurately (Nightingale & Douglas, 2018).

The inclusion of wearables that measure external load variables in competitive sport programming may be an avenue for coaches and sport medicine practitioners, researchers, and strength and conditioning coaches to meaningfully track athletes' performance in a way that extends beyond internal load methods—like subjective perceived ratings of exertion and heart rate measurement. External load refers to the interaction of volume and intensity that athletes experience during their sport, and often refers to the work performed by an athlete (Wallace, Slattery, & Coutts, 2009). Typically, the quantification of this 'work' (i.e., movement demands) is captured through GPS, accelerometers, and/or video analysis. To date, the precision, reliability, and accessibility of GPS and accelerometers continue to improve, which has allowed sport science practitioners to use them at the highest levels of sport. For example, in 2015, the Federation Internationale de Football Association (FIFA) for men's and women's soccer allowed the collection of data during competitive matches using GPS (Jones & Denison, 2018). Similarly, elite rugby league players wore GPS to capture physical demands during competitive matches (Gabbett, 2013). Despite its prevalence in other team sports, the adoption of wearables by key decision-makers in ice hockey, including managers, coaches, and players, has been less immediate. This may be related to the limited empirical research on the degree of transferability between playing surfaces (i.e., ground compared to ice). Additionally, there are other administrative, financial, and logistical constraints that likely play a role in this slow uptake and implementation in the sport of ice hockey.

In the evolving climate of sport, the question of which statistics should be used has become a more important question than whether statistics should be used when it comes to many facets of decision-making. In the context of wearables, selecting which metrics to use has become a critical question. The value lies in the determination and prioritization of the key metrics for each sport that yield the most information, value, validity, reliability, and predictive capabilities. For example, Gabbett highlighted that valuable information was gleaned by comparing match data from wins and losses in team sports (Gabbett, 2013). Specifically, the physical demands in elite rugby, measured using GPS and accelerometers, were higher when the team was winning versus losing, and when competing against lower ranked teams (Gabbett, 2013). Although this study focused on rugby, the findings suggest that success in matches is linked to the team's ability to maintain a higher playing intensity and may also be applicable to the sport of ice hockey. Similar findings in other team sports support the notion that player output varies depending on the result of the match. In soccer, it has been shown that high-intensity activity by key positions had a positive impact on winning (Andrzejewski, Chmura, Konefal, Kowalczuk, & Chmura, 2018; Vigne et al., 2013). The timing of these high-intensity events in soccer has also been shown to have a relationship with winning, as teams who display higher peak and mean running speeds in the second half of the game have a greater likelihood of winning the match (Konefal et al., 2019).

Findings such as these could have direct implications for practice and competition strategies. Even slight changes to tactical strategies, athlete workload, and performance outputs may play a vital role in the outcome of a competition (e.g., shift changes and in-game strategies). Match outcome and its relationship to physical and tactical performance has been widely studied in other team sports (Andrzejewski et al., 2018; Bloomfield, Polman, & O'Donoghue, 2005; Gabbett & Gahan, 2016; Konefal et al., 2019; O'Donoghue & Tenga, 2001; Wallace et al., 2009), allowing coaches and sport scientists to prepare more effective training and competition strategies to have a positive impact on performance outcome. The application of wearable technology in elite ice hockey is an area of potential growth in sport science, with recent work exploring the difference between external and internal metrics between training and competition. Differences were evident when comparing data between playing positions, with defense having lower outputs of PlayerLoad, PlayerLoad·min^{-1}, Training Impulse (TRIMP), and explosive efforts compared to forwards (Douglas, Rotondi, Baker, Jamnik, & Macpherson, 2019). For the sport of ice hockey, there remains a void in the literature examining the playing conditions for elite level teams. The integration of player tracking technology at all levels of the sport has the potential to modernize the landscape of hockey analytics. Specifically, the inter- and intra-player and positional differences within and between competitive matches appear to be under-represented in the literature. Therefore, the primary aim of this study is to examine differences captured by wearable technology through inertial movement sensors worn by athletes in ice hockey matches. The hypothesis is twofold; higher player movement and intensity plays a role in match outcome, as well as player movement and intensity decrease across the game.

Materials and Methods

Study Design

A mixed effects design was employed to investigate the differences in on-ice measures of external load during competition, and whether these measures differed based on the outcome of the game (i.e., win or loss) by period of play, and the interaction of match outcome and period. This study used a retrospective, secondary data analysis with on-ice metrics for all 20 athletes collected during Hockey Canada's Senior National Women's Team matches during the 2016–2017 season. The team participated in 26 matches, with an outcome of 13 wins and 13 losses. Data were averaged for each position and reported for all three periods of play to allow for a repeated measures design comparing the differences specifically between match periods.

Participants

Elite female ice-hockey players (age = 24.8 ± 3.5 years; height = 171.6 ± 6.1 cm; body mass = 71.1 ± 6.1 kg) who represented their country in exhibition and international matches participated in this study. Using Baker and colleague's taxonomy (Baker, Wattie, & Schorer, 2015), this sample of athletes would be considered 'expert' based on their highest level of competition at the international level. The sample consisted of 13 forwards and 7 defensive players. Goalies were excluded from the analysis due to their unique movement characteristics. All subjects gave their written informed consent for inclusion before they participated in the study. The study was conducted in accordance with the Declaration of Helsinki and was granted ethics exemption by the York University Office of Research Ethics on the basis that it consisted of secondary analysis of existing data and did not contain any identifying information.

Procedure

Each athlete wore a trunk-mounted (strapped to chest) Catapult S5 unit (Catapult Sports, Melbourne, Australia; firmware version 7.27) in a monitor-specific vest worn tight against the body in compliance with the manufacturer's guidelines. The integration of 100-Hz triaxial accelerometry (quantifies linear motion in all directions—acceleration and deceleration) with triaxial 100-Hz gyroscopes (sampled at 2000° per second to measure body angular motion and rotation) and 100-Hz triaxial magnetometers (measures direction and orientation of body position) allowed for the quantification of PlayerLoad during indoor activity (Boyd, Ball, & Aughey, 2011; Van Iterson, Fitzgerald, Dietz, Snyder, & Peterson, 2017). The triaxial gyroscope and magnetometer functions are necessary in the aggregation of data from each specific axis in the mediolateral, vertical, and anteroposterior planes of motion to quantify PlayerLoad during dynamic multi-plane body movement (Van Iterson et al., 2017). Data from the Catapult S5 units were downloaded to a database maintained by the National Sports Organization. Catapult OpenField software (OpenField 1.17.0 Catapult Sports, Melbourne, Australia) was used for proprietary postprocessing. Previous studies have reported the Catapult Sports S5 to have an excellent intradevice reliability for PlayerLoad values, with most Coefficient of Variation (CV) values rating low (<1.0%) (Nicolella, Torres-Ronda, Saylor, & Schelling, 2018; Van Iterson et al., 2017). It has also been reported that Intraclass Correlation Coefficient (ICC) ranged from 0.8 to 1.0 for intradevice comparison (Nicolella et al., 2018).

External Load Metrics

A description of the metrics used in the analysis are:

PlayerLoad is the summation of accelerations across all movements, divided by 100 (Nicolella et al., 2018). This was expressed as total load (arbitrary units (au)). It is calculated as:

$$\text{PlayerLoad} = \sqrt{\frac{(a_{y1} - a_{y-1})^2 + (a_x - a_{x-1})^2 + (a_z - a_{z-1})^2}{100}}$$

where: a_y = Anteriorposterior acceleration; a_x = Mediolateral acceleration; a_z = Vertical acceleration.

Skating load is the summation of all peak accelerations recorded during the skating stride. Skating load is derived from a proprietary algorithm to identify the hockey stride based off the accelerometer tracing, gyroscope, and magnetometer sensors. The corresponding resultant acceleration peaks are calculated and multiplied by the athlete's mass. This was expressed as total load (arbitrary units (au)). It is calculated as:

$$\text{Skating Load} = \left(\sqrt{\left(a_y\right)^2 + (a_x)^2 + (a_z)^2} \times \text{Player Mass}\right)/100$$

Explosive efforts is the frequency of how many explosive movements were performed. High-intensity movements included: Rapid accelerations and decelerations, high-intensity skating, rapid changes of direction (skating-based or body contact), and high-intensity shots made by the player. This count was derived from Inertial Movement Analysis (IMA) data. Once identified, the sum of the X, Y area was calculated and expressed as the event magnitude ($m \cdot s^{-1}$) (Meylan, Trewin, & McKean, 2017). Any identified movement that occurred at a rate greater than 2 $m \cdot s^{-1}$ in any direction was considered an explosive effort (Douglas et al., 2019).

Explosive ratio is a ratio calculated by taking the total number of explosive efforts and dividing it by PlayerLoad. This provides information as to the athletes' ability to produce explosive movements based off their total load accumulation throughout the course of a match.

Percentage high force strides captures the percentage of all the ice hockey strides that occurred in the high force band. For female ice hockey players, strides that exceed 140 au skating load are coded as high force strides based off banding recommendations from the manufacturer.

Statistical Analysis

For each variable listed above, a two-factor mixed effects ANOVA was performed to investigate the difference in matches that were won and lost, as well as the difference in variables across the three periods of play. A normal distribution of data was examined using the Shapiro-Wilk's test and homogeneity of variance was confirmed with Levene's test, which supported the use of parametric methods of analysis. Due to the differences in match demands, forwards and defensive players were analyzed separately. All data were processed in RStudio (version 1.0.153, R Core Team, Vienna, Austria). Differences between match outcome as well as between periods were analyzed using effect size (ES) statistics. To ensure consistency in reporting of results and comparability across all analyses, the partial eta-squared statistics from ANOVA were also converted to ES (Cohen, 1988). Effect sizes were categorized using the following descriptors: <0.2—trivial, 0.2–0.6—small, >0.6–1.2—moderate, >1.2–2.0—large, >2.0—very large (Hopkins, Marshall, Batterham, & Hanin, 2009). Data are presented as mean ± SD and statistical significance was set at $p \leq 0.05$.

Results

Descriptive Summary of On-Ice Metrics and Two-Way ANOVA Results

The descriptive statistics for the different metrics are summarized in Table 5.1 for forwards and Table 5.2 for defense. The results of the two-way mixed effect ANOVAs can be found in Table 5.3 for forwards and Table 5.4 for defense.

Table 5.1. Descriptive statistics of select external load variables for forwards, by game. outcome and period.

Select External Load Variable—Forwards			**Mean**	**SD**
PlayerLoad	Win	First Period	692.82	104.65
		Second Period	674.30	92.97
		Third Period	667.37	112.58
	Loss	First Period	716.04	112.00
		Second Period	659.79	134.08
		Third Period	714.52	139.19
Skating Load	Win	First Period	527.24	20.39
		Second Period	493.04	39.50
		Third Period	484.94	37.97
	Loss	First Period	517.88	26.57
		Second Period	467.11	67.58
		Third Period	498.78	80.97
Explosive Efforts	Win	First Period	1043.31	143.74
		Second Period	968.92	133.20
		Third Period	945.62	138.93
	Loss	First Period	1045.54	118.49
		Second Period	907.08	185.36
		Third Period	981.46	194.42
Explosive Ratio	Win	First Period	1.51	0.10
		Second Period	1.44	0.09
		Third Period	1.43	0.11
	Loss	First Period	1.47	0.10
		Second Period	1.38	0.07
		Third Period	1.37	0.13
Percentage High Force Strides	Win	First Period	17.70	1.21
		Second Period	17.11	1.24
		Third Period	17.00	1.43
	Loss	First Period	16.41	1.78
		Second Period	16.25	1.99
		Third Period	16.78	2.26

Table 5.2. Descriptive statistics of select external load variables for defense, by game. outcome and period.

Select External Load Variable—Defense			Mean	SD
PlayerLoad	Win	First Period	363.19	60.04
		Second Period	358.43	58.29
		Third Period	346.64	65.55
	Loss	First Period	371.37	54.99
		Second Period	346.59	50.51
		Third Period	354.61	65.96
Skating Load	Win	First Period	477.76	48.48
		Second Period	453.19	52.43
		Third Period	434.41	49.62
	Loss	First Period	484.66	59.74
		Second Period	453.41	82.51
		Third Period	445.38	98.04
Explosive Efforts	Win	First Period	478.23	77.25
		Second Period	449.31	87.78
		Third Period	421.38	88.47
	Loss	First Period	486.92	53.47
		Second Period	438.77	58.53
		Third Period	429.38	103.46
Explosive Ratio	Win	First Period	1.32	0.11
		Second Period	1.25	0.13
		Third Period	1.21	0.13
	Loss	First Period	1.32	0.13
		Second Period	1.27	0.09
		Third Period	1.21	0.19
Percentage High Force Strides	Win	First Period	10.20	2.00
		Second Period	10.21	2.41
		Third Period	9.93	1.99
	Loss	First Period	10.45	2.40
		Second Period	10.55	2.39
		Third Period	10.49	2.44

Table 5.3. Two-way ANOVA results of select external load variables on game outcomes and periods for forwards.

Select External Load Variables—Forwards		F-Statistic	*p*	ES
PlayerLoad	WinLoss	F(1,72) = 0.48	0.48	0.20
	Period	F(2,72) = 0.51	0.51	0.29
	WinLoss:Period	F(2,72) = 0.63	0.63	0.20
Skating Load	WinLoss	F(1,72) = 0.39	0.53	0.20
	Period	**F(2,72) = 4.92**	**0.01**	**0.75**
	WinLoss:Period	F(2,72) = 1.02	0.37	0.35
Explosive Efforts	WinLoss	F(1,72) = 0.05	0.82	0.06
	Period	**F(2,72) = 3.35**	**0.04**	**0.63**
	WinLoss:Period	F(2,72) = 0.68	0.52	0.29
Explosive Ratio	**WinLoss**	**F(1,72) = 5.30**	**0.02**	**0.26**
	Period	**F(2,72) = 6.63**	**0.002**	**0.87**
	WinLoss:Period	F(2,72) = 0.10	0.91	0.02
Percentage High Force Strides	**WinLoss**	**F(1,72) = 4.21**	**0.04**	**0.50**
	Period	F(2.72) = 0.33	0.72	0.20
	WinLoss:Period	F(2,72) = 0.65	0.52	0.29

Note: Bold font indicates $p < 0.05$.

Table 5.4. Two-way ANOVA results of select external load variables on game outcomes and periods for defense.

Select External Load Variables—Defense		F-Statistic	*p*	ES
PlayerLoad	WinLoss	F(1,72) = 0.02	0.89	0.06
	Period	**F(2,72) = 4.51**	**0.01**	**0.70**
	WinLoss:Period	F(2,72) = 0.08	0.92	0.09
Skating Load	WinLoss	F(1,72) = 0.15	0.69	0.09
	Period	F(2,72) = 2.52	0.08	0.50
	WinLoss:Period	F(2,72) = 0.04	0.96	0.06
Explosive Efforts	WinLoss	F(1,72) = 0.01	0.91	0.06
	Period	**F(2,72) = 3.45**	**0.04**	**0.63**
	WinLoss:Period	F(2,72) = 0.12	0.89	0.11
Explosive Ratio	WinLoss	F(1,72) = 0.02	0.89	0.06
	Period	**F(2,72) = 4.51**	**0.01**	**0.70**
	WinLoss:Period	F(2,72) = 0.08	0.92	0.09
Percentage High Force Strides	WinLoss	F(1,72) = 0.55	0.46	0.20
	Period	F(2.72) = 0.04	0.96	0.06
	WinLoss:Period	F(2,72) = 0.03	0.97	0.06

Note: Bold font indicates $p < 0.05$.

PlayerLoad

For the defensive players, there was no statistically significant difference between wins and losses, however, a statistically significant difference was found between periods (F(2,72) = 4.51, $p = 0.01$, ES = 0.70), with the first period having the highest PlayerLoad (482.58 ± 65.24), followed by the second period (444.04 ± 73.29) and third period (425.38 ± 94.40). Post hoc testing using Tukey HSD indicated there was a moderate decrease from the first period to third period ($p = 0.01$, ES = 0.70).

Skating Load

For forwards, a two-way ANOVA identified a statistically significant difference for skating load between periods (F(2,72) = 4.92, $p = 0.01$, ES = 0.75), with the first period having the highest load (522.56 ± 23.70), followed by the third period (491.86 ± 62.36), with the second period demonstrating the lowest load (480.1 ± 55.82). Post hoc testing using Tukey HSD indicated a moderate decrease from the first to second period ($p = 0.01$, ES = 0.98).

Explosive Efforts

There was a statistically significant difference for explosive efforts between periods for the forwards (F(2,72) = 3.35, $p = 0.04$, ES = 0.63), with the first period having the highest rating (1044.42 ± 129.06), followed by the third period (963.54 ± 161.25), and second period (938.00 ± 161.25). Post hoc testing using Tukey HSD indicated that there was a moderate decrease from the first period to second period ($p = 0.04$, ES = 0.73).

For defensive players, a statistically significant difference between periods was also found (F(2,72) = 3.45, $p = 0.04$, ES = 0.63), with the first period reporting the highest explosive efforts (482.58 ± 65.24), followed by the second period (444.04 ± 73.29) and the third (425.28 ± 94.40).

Post hoc testing using Tukey HSD showed there was a moderate decrease between the first period and third period (p = 0.03, ES = 0.71).

Explosive Ratio

For forwards, there was a main effect of match outcome (F(1,72) = 5.30, p = 0.02, ES = 0.26), such that the average explosive ratio in matches that were won were higher (1.46 ± 0.10) than lost (1.41 ± 0.11). There was a statistically significant difference between periods (F(2,72) = 6.63, p = 0.002, ES = 0.87), with the first period demonstrating the highest explosive ratio (1.49 ± 0.10), followed by the second (1.41 ± 0.09) and the third (1.40 ± 0.12). Post hoc testing using Tukey HSD indicated a moderate decrease from the first period to both the second (p = 0.01, ES = 0.84) and third periods (p = 0.004, ES = 0.81).

For defensive players, there was a main effect of period number (F(2,72) = 4.51, p = 0.01, ES = 0.70), whereby the first period reported the highest explosive ratio (1.32 ± 0.12), followed by the second (1.26 ± 0.11) and third (1.21 ± 0.16). Post hoc testing using Tukey HSD showed a moderate decrease between the first period and third period (p = 0.01, ES = 0.78).

Percentage High Force Strides

The forward group showed a statistically significant difference between match outcome (F(1,72) = 4.21, p = 0.04, ES = 0.51), where a higher percentage of high force strides were found in matches that were won (17.27 ± 1.30) compared to matches that were lost (16.48 ± 1.98).

Discussion

In this study, we report data from wearable technology using selected metrics of external load collected during matches, and their differences based on match outcomes across three periods of play. Our results generally support the use of wearable technology for collecting player data related to volume and intensity, as measured through various metrics of external load. When examining the relevance to match outcome, indices of external load appears to be an important factor in this sample of elite female ice hockey players, but only among the forwards where a significant difference for explosive ratio and the percentage of high force strides was found in matches that were won versus lost. Both are indicators of on-ice skating intensity, suggesting that the ability to have a high output of skating intensity is important for success in matches.

The results also demonstrate a significant drop in external load measures from the first period to the second period. The second period had lower measured skating load and explosive efforts compared to the first and third period. With the sport of ice hockey being broken up into three 20-min periods interspersed with a 15-min intermission, one could surmise that the drop-off would be similar across the later periods due to the intermission, which affords the athletes the ability to rest and recover. Evidence of this declining output was seen in the defensive group, where significant differences in period output was found in PlayerLoad, explosive efforts, and explosive ratio. In all three of these variables, the first period had the highest output and the third period the lowest, which might be attributed to the accumulation of fatigue. The recent work by Lignell and colleagues (2018) in men's ice hockey using video-based external load monitoring supports evidence of declining outputs because of fatigue. The researchers showed that the average sprint-skating speed was lower in the later periods of the match (Lignell, Fransson, Krustrup, & Mohr, 2018). There may be several explanations as to why this occurs in ice hockey. One reason could be the inability to repeat the appropriate number of high-speed bouts within a hockey match. It has been shown in ice hockey players that a high aerobic power increases the ability to recover from repeated bouts of anaerobic power (Stanula, Roczniok, Maszczyk, Pietraszewski, & Zajac, 2014). Peterson and colleagues (2015) found a high correlation between maximal oxygen uptake and fatigue during the later periods of a mock hockey match in high-level collegiate hockey players (Peterson et al., 2015). Another explanation could be attributed to the tactical situation of the match during the later phases of competition. If a team is winning, the team may adjust their strategy to play more conservatively, which could alter player output, unrelated to fitness or fatigue. In most high-level ice hockey, coaches prefer to play an assertive style forecheck when the score is close to attack the opponent and increase the pace of play. This up-tempo style relies on a fast-skating aggressive style of forecheck most coaches employ from a tactical perspective (Dennis & Carron, 1999).

Another interesting finding from on-ice tracking data of men's professional ice hockey reported players performed an average of seven high-intensity skating bouts every minute (Lignell et al., 2018), which is proportionally much higher than reported in other field and court-based team sports (Krustrup & Mohr, 2015; Povoas et al., 2014; Scanlan, Dascombe, Reaburn, & Dalbo, 2012). According to the published TMA literature for female ice hockey, forwards had an average of 18 forward shifts per match, with a mean duration of 48 s; whilst their defensive teammates averaged 15 defensive shifts per match with an average shift duration of 43 s. Each shift consisted mainly of low- to moderate-intensity skating interspersed with brief, intermittent high-intensity bouts (Jackson & Gervais, 2016).

Additionally, other studies have assessed the physiological demands of ice hockey during competition. In conjunction with aerobic training, it has also been shown that a positive relationship exists between ice hockey players with higher anaerobic power scores and their draft position in the National Hockey League (Burr et al., 2008). Both are related to the outputs required for individual on-ice success, (i.e., the ability to produce high-intensity output and to repeat the high-intensity bouts). The finding that positional differences relate to match outcome did not come as a surprise, as it has been reported that the match demands placed on forwards and defense are vastly different (Douglas et al., 2019). Female ice hockey forwards have been found to have greater anaerobic power output, as well as a higher aerobic capacity, when compared to female ice hockey defensive players (Geithner, Lee, & Bracko, 2006), along with a higher duration and frequency of high-intensity skating than defensive players (Jackson & Gervais, 2016). These differences are most likely attributed to the different positional demands, whereby the defensive group retreats more often and typically covers a lower proportion of the ice. Positional differences were also reflected in men's professional ice hockey, with forwards exhibiting a higher average skating speed and covering a greater distance at high-intensity (Lignell et al., 2018). Taken together, it appears that for success in ice hockey, it is important for players to be able to tolerate high-intensity and high-velocity efforts, as well as the ability to endure repeat anaerobic bouts. This can have important implications for coaches and sport medicine practitioners alike to help inform periodized training and competition practices, especially as it relates to match outcomes.

To the authors' knowledge, this is the first study of its kind to examine wearable technology during competitive matches in the sport of women's ice hockey. Some studies have examined the physiological demands in relation to team success in ice hockey (Green, Pivarnik, Carrier, & Womack, 2006), however, this study is unique in that multiple performance metrics were assessed via wearable technology (PlayerLoad, skating load, explosive efforts, explosive ratio, and percentage high force strides). While our study is novel in terms of using measurable match data from accelerometers to uncover determinants of match play and match outcome, there are certain limitations that are important to acknowledge. The first is the length of time the data were collected. Increasing the study length to include multiple seasons with the same athlete sample and coaching staff could allow for patterns to emerge, both from the main effects and the interactions between winning and losing and player metrics during different periods of the game. A second limitation is that due to the variable nature of player deployment in ice hockey, large standard deviations were present. Player ice time is largely dictated by coaching strategy, and thus using a positional average dataset can be limiting. Further research could focus on the higher-performing players (e.g., top six forwards and top four defense). Furthermore, while the inclusion of high-level athletes allowed for a unique and valuable data set, it limits the generalizability of our results to other populations, such as a non-expert group of ice hockey players, which would allow researchers to track changes between levels of performance.

Conclusions

The results of the present study demonstrate the potential benefits of using wearable technology to collect data on performance metrics in the sport of ice hockey. With appropriate assessment and implementation, it may positively impact coaches' decision-making as it pertains to game demands and game outcome. The results suggest the intensity measure of external load of game play by forwards has an impact on match outcome. Secondary results show between-period differences for forwards with the second period typically lower in external load measures than the first period or third period. For defensive players, a difference in external load across all three periods was evident, with the main findings suggesting a drop-off between the first and third periods. There is a paucity of research in the application of wearable technology to monitor external load in ice hockey, and as the body of research grows it will be important to understand the unique movement patterns and movements strategies that are inherent to ice hockey, such as the impact of low-intensity locomotion or gliding and its relationship to skating performance.

Future research could further investigate the reasons behind the decreased output across a match to determine if it is physiological fitness- or fatigue-related, as well as explore the use of some of the between-period interventions utilized by other high-performance teams in other sports.

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CHAPTER SIX: DISCUSSION

6.1 Main Findings

Each of the three preceding chapters in this dissertation addresses gaps in both the research field regarding applied work in the sport of ice hockey and in female athletes who play at the highest level of competition. This was accomplished using the ARMSS model to provide structure to the research process. The first manuscript, titled "On-Ice Physical Demands of World-Class Women's Ice Hockey: From Training to Competition" was written to underpin this stage of the ARMSS. The purpose of this paper was to provide descriptive measures for coaches to make informed decisions regarding volume and intensity in relation to training and match demands between and within each of the two skating positions. The first major finding was that there were differences in external and internal load measures between training and competition for each of the skating positions. Forwards had both higher volumes and intensities of load measures than defense in both training and competition. Furthering our understanding of the on-ice demands of training and competition, it was found that apparent differences exist between sub-elite and elite athletes in measures of external load. The second manuscript, titled "A Comparison of On-Ice External Load Measures between Sub-Elite and Elite Female Ice Hockey Players" builds further on the concept of understanding the demands of the sport for coaches. This paper provides valuable information that can assist sports performance professionals with identified development requirements for sub-elite athletes. The development of technical game-play differences between elite and sub-elite developmental athletes has been identified as a crucial potential performance indicator to track as athletes progress in their sport and could have relevance for talent identification (Woods, Bruce, Veale, & Robertson, 2016). With a paucity of published data on female ice hockey, it is essential to build a strong foundation of applied literature using various cross-sectional studies to fortify what becomes the base of the applied research field for both wearable technology and on-ice performance indicators in elite female ice hockey. These cross-sectional studies will also provide insight to the applied practitioner to explore various performance metrics in relation to performance, while also underpinning future work in wearable technology in male and female ice hockey.

The third manuscript, "On-Ice Measures of External Load in Relation to Match Outcome in Elite Female Ice Hockey", builds off the previous works to provide an initial exploration into the realm of performance-outcomes based off wearable data. Elite female ice hockey players performed a higher number of high-intensity movements in both training and competition. These differences were evident across both positions, as elite ice hockey players had significantly higher measures for intensity-based external load metrics. The importance of on-ice intensity was additionally supported by examining external load measures in relation to match outcome. Among forwards, a significant difference was found for explosive ratio and percentage of high force strides. Both are indicators of on-ice skating intensity, suggesting that the ability to have a high output of skating intensity is vital for success in matches. Taken together, this information is valuable for athletes, coaches, and sports scientists working in the sport of ice hockey as it provides valuable information related to level of play, normative data from training and competition, as well as revealing critical aspects of performance in relation to performance enhancement. These studies contribute to reducing the gap in our understanding of elite female athletes and address the lack of information on wearables in ice hockey.

Wearable technology has afforded sports practitioners an alternative means to measure and monitor the work performed during training and competition. TMA studies are well-established methods of reporting differences in workload and player output in ice hockey, and technology has allowed for the use of optical tracking using artificial intelligence to report training load during matches (Lignell et al., 2018). Both observational-based techniques have strengths and limitations, many of which can be overcome using wearable technology. Wearable technology provides an objective measure of the internal and external work being performed by the athlete, without relying solely on the subjective evaluation of the observer. Furthermore, the literature regarding internal and external training load monitoring using wearables across a multitude of sports has recently increased significantly (Cardinale & Varley, 2017). Training load research is skewed towards outdoor team sports, which makes it harder for sport scientists and coaches in indoor sports to draw comparative conclusions from outdoor sports. By contributing peer-reviewed work involving wearable technology specific to ice hockey, we have been able to help minimize the barriers of applied sport science, including a) the lack of relevance, b) failure to address relevant questions, and c) the dissemination of findings that are too difficult to apply by creating knowledge that is could be relevant to coaches and practitioners within the sport (Gabbett et al., 2017).

A strong foundation of wearable technology-based research in ice hockey will allow the field to explore different methods of how training load can impact player performance, development, and potential injury prevention. Without descriptive studies, practitioners will not be able to have comparative data to build further research questions, nor will they have the ability to inform and progress the field through the upper stages of the ARMSS (Bishop, 2008). This foundation of descriptive studies, including the normative training and competition data of both sub-elite and elite athletes, along with the establishment of important on-ice metrics, will allow future works to continue to progress the research on wearables in ice hockey. Once the research foundation is established, the applied sports science field can produce further literature focusing on performance predictors. The field of wearable technology in ice hockey can include studies that investigate the relationship between predictor variables and actual sports performance (Bishop, 2008). With the relationship found between on-ice skating intensity in forwards with a favourable match outcome, practitioners can use this information as feedback into both styles of play and increased focus on training intensities to mirror match demands.

6.2 Practical Application

The results of this research project have implications for potential positive change in the preparation of ice hockey athletes on the individual level, at the level of coaching, and within the research community of applied sports science. At the individual level, the results of this project may inform female ice hockey players of objectively measured on-ice movement characteristics of those that play the sport at the highest level. With the comparison between elite and sub-elite ice hockey players, this could have a potential impact on the developmental pathway as developing athletes have specific targets to achieve. At the coaching level, this information can help to gain a broader understanding of match and training demands. As mentioned in the introduction, reasons for the lack of transfer from research to practice include outdated coaching education as well as a lack of confidence in the research methods. Traditionally, ice hockey coaches are often slow to change their ways, and often at the expense of their athlete development. Typically, volume, or duration of practice, dictate the amount and intensity of training sessions. However, the focus of training sessions should be on intensity as it has been shown to have both a positive effect on winning, but it also may be essential for sub-elite athletes to be exposed to intensity to enhance their on-ice development. A better understanding of the movement demands within the team could eliminate unnecessary training for general purposes and focus practice preparation intensities to closer resemble game demands.

With the rate of development in wearable technology, adoption and integration is continuing to increase across all levels of sport (Taylor et al., 2012). As technology advances, the amount of information that can be measured during training and competition has the potential to transform the sport. Local Positioning Systems (LPS), which are indoor satellites installed into indoor stadiums are starting to become commonplace in the National Hockey League. The use of positional systems in ice hockey offers a myriad of research opportunities. These include looking at match-to-match variations of speed and distance outputs, and a more in-depth look at situational gameplay. As more training load data become available, the ability to process and handle vast amounts of data will become paramount. The method(s) used to analyze the datasets will increase in complexity, and techniques such as machine learning and advanced neural networks could be used more frequently in the analysis of ice hockey data.

The results of this project can be used to form the cornerstone of load monitoring in both female ice hockey as well within the applied sports science field. The concept of load monitoring for elite sport is quite prevalent in a plenitude of other sports. The research literature has many examples of how load monitoring has improved performance (Borresen & Lambert, 2009; Buchheit et al., 2013) and the reduction of injury (Hulin, Gabbett, Lawson, Caputi, & Sampson, 2016; Soligard et al., 2016). The information collected and presented in this project will hopefully lay the foundation for further applied sports science in ice hockey, which is under-represented in applied research.

6.3 Strengths

These findings make substantial contributions to the applied sports science literature for ice hockey. They were novel in terms of the sport (ice hockey), participant/gender group (elite female athletes), and technology used (accelerometers). More specifically, elite athlete research, especially research focusing on elite female athletes, is rare. The results presented in Chapter Three and Chapter Four are particularly important as they provide on-ice normative data measured by athletes both at the top of their level of competition, but also athletes who are on a developmental pathway. Previous literature involving elite female ice hockey players has focused on physical and physiological measures (Douglas, 2015; Ransdell & Murray, 2011; Ransdell et al., 2013) measured through physical testing. Another strength of these findings is the robust and longitudinal dataset that was analyzed. The data that was sampled spanned four years of training and competition, including the lead-up and competition during the Olympic Games, as well as three different World Championship tournaments.

6.4 Limitations

This research project has several limitations, which are discussed in each chapter. Firstly, only forwards and defensive athletes were included in each of the chapters. Goalies were excluded due to the nature of the movement demands associated with this unique position (Geithner et al., 2006). Future works that focus on goalie-specific movement demands from wearable technology in training and competition would be novel and could produce information not readily available in the literature. While the large and robust dataset across four competitive seasons was identified as a strength, this dataset was also limited in that seasons were viewed independently of each other. Future longitudinal studies examining training load in ice hockey could investigate the natural fluctuations that occur over a competitive season and compare various portions of the season. For example, pre-season volume and intensity could be higher than during the regular season or various portions of the yearly calendar.

Lastly, the technology used in this study, while shown to be valid and reliable in ice hockey (Van Iterson et al., 2017), was not put through the rigors of test-retest reliability as that was outside the scope of this applied study. Care was taken to follow best practices of data collection and assurances to match methods of previously published validity and reliability studies. For example, athletes wore the units in a monitor-specific vest worn tight against the body in compliance with the manufacturers guidelines as well as previous literature on the validity of the units (Boyd, Ball, & Aughey, 2011; Van Iterson et al., 2017). To control for interunit reliability, all athletes wore the same unit for every session in each season in order to provide consistency for comparison and as an attempt to limit the impact of inter-device variability as recommended by Nicolella and colleagues. (Nicolella et al., 2018).

CHAPTER SEVEN: CONCLUSION

The information contained within the dissertation, along with the subsequent published material, provides a solid groundwork for the continued pursuit of applied sports science in ice hockey. Each of the studies contributes to the existing evidence of athlete monitoring and athlete preparation using wearable technology and the study of elite female athletes. Further, this body of research contributes to our understanding of external load and performance measured using wearable technology.

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APPENDIX A: ACCEPTED MANUSCRIPT IN JOURNAL FORMAT (*IJSPP*)

Purpose: To compare on-ice external and internal training loads in world-class women's ice hockey during training and competition. ***Method:*** On-ice training load were collected during one season from 25 world-class ice hockey players via wearable technology. A total of 105 on-ice sessions were recorded, which consisted of 61 training sessions and 44 matches. Paired and unpaired t-tests compared training and competition data between and across playing positions. ***Results****:* For training data, there was a difference between positions for PlayerLoad ($p < .001$, ES = 0.32), PlayerLoad·min^{-1} ($p < .001$, ES = 0.55), Explosive Efforts ($p < .001$, ES = 0.63), and TRIMP ($p < .001$, ES = 0.48). For the competition data, there were also differences between positions for PlayerLoad ($p < .001$, ES = 0.26), PlayerLoad·min^{-1} ($p < .001$, ES = 0.38), Explosive Efforts ($p < .001$, ES = 0.64), and TRIMP ($p < .001$, ES = 1.47). Similar results were found when positions were viewed independently, competition had greater load and intensity across both positions for PlayerLoad, TRIMP, and Explosive Efforts ($p < 0.001$, ES = 1.59 – 2.98); and with PlayerLoad·min^{-1} ($p = 0.016$, ES = 0.25) for the defense. ***Conclusions:*** There are clear differences in the volume and intensity of external and internal workloads between training and competition sessions. These differences were also evident when comparing the playing positions, with defense having lower outputs compared to forwards. These initial results can be used to design position-specific drills that replicate match demands for ice hockey athletes.

Keywords: Female, International, Monitoring, Technology, Team Sport, PlayerLoad

On-Ice Physical Demands of World-Class Women's Ice Hockey: From Training to Competition

The sport of ice hockey is characterized by athletes repeatedly performing high-intensity, short-duration efforts, while maintaining highly complex movements over the course of a 60-minute competition. For optimal performance, ice hockey athletes need to have well-rounded physical and physiological capabilities including high aerobic and anaerobic capabilities, muscular strength, power, and endurance.[1] These physiological qualities are expressed in ice hockey by combining dynamic skating movement patterns with skills such as skating, shooting, and passing of the puck.[2]

The prevailing method to measure work performed on the ice in hockey research is through time-motion analysis (TMA). This involves setting up video recording equipment, monitoring players' movements, and categorizing them according to their intensity. According to the published TMA literature for female ice hockey, forwards had an average of 18 forward shifts per game, with a mean duration of 48 seconds; whilst their defensive teammates averaged 15 defensive shifts per game with an average shift duration of 43 seconds. Each shift consisted mainly of low- to moderate-intensity skating interspersed with brief, intermittent high intensity bouts; with a mean shift heart rate (HR) of 92% of player's maximum HR.[3] TMA has been widely used across many team sports,[3–5] but is often criticized when applied to sports where player movements are extremely explosive and short in duration, and therefore are difficult to record accurately.[2] Reliability of TMA is often dependent on the observer, and therefore can vary greatly based on the number of observers, expertise of the observer, and the level and sport being observed.[6]

One potential solution to objectively quantify the movement demands in sport has been to outfit athletes with wearable technology. Due to the indoor nature of ice hockey, the use of Global Positioning System (GPS) devices is not suitable to measure the movement demands of players due to the inability to connect to satellites. Emerging research using technological advancements that incorporate triaxial accelerometry, along with the recordings of the gyroscope and magnetometer, can successfully quantify sport-specific movements.[7] One such method to quantify the workload performed by an athlete is PlayerLoad, which sums the individual triaxial accelerometer vectors to produce an instantaneous measure of work rate, expressed in arbitrary units. PlayerLoad is calculated by using the measurements recorded via a Minimaax™ unit (Catapult Sports, Melbourne, VIC, Australia) and is defined as the "square root of the sum of the squared instantaneous rate of change in acceleration in each of the three vectors (X, Y, and Z axis) and divided by 100".[8] PlayerLoad has been used to describe the physical and physiological demands of sports such as Australian rules football, basketball, netball, rugby, cricket, and soccer.[8–12] Understanding the activity profile of a sport and quantifying the disparity between training and competition demands allows coaches and practitioners to enhance their understanding of the underlying physical and physiological load placed on the athletes. The comparison of training and competition demands can improve a coach's ability to apply a scientific framework of periodization to training programs.

To date, only one published paper has investigated the use of PlayerLoad in men's ice hockey. Van Iterson and colleagues examined the test-retest reliability of PlayerLoad during nine ice hockey tasks in a simulated game-like condition. They reported moderate-to-large test-retest reliability when using PlayerLoad to quantify on ice movements (CV 2.2-13.8%).[13] The movement demands associated with the skating stride are inherently different than running or sprinting, as skating requires the lower limbs to move in the posterolateral plane with a large demand placed on the hip extensors, hip abductors and hip adductors. Due to the low coefficient of friction of the ice, the forward propulsion in skating needs to be perpendicular to the gliding direction of the skate, which leads to more horizontal and lateral force production than running or sprinting.[14]

As with the use of any technology or measuring equipment, it is imperative that the devices are valid and reliable. The Minimaax^{TM} device has been found to have an excellent intradevice reliability for PlayerLoad values, with the majority of CV values <1.0%. It has also been reported that Intraclass Correlation Coefficient (ICC) ranged from 0.8 to 1.0 for intradevice comparison.[15] Along with PlayerLoad, inertial movement analysis (IMA) has been used to identify explosive actions in sports. In order for an event to register as an IMA event, there are two criteria that must be met; magnitude and direction. Inertial movement analysis data has been shown to be a valid and reliable measure to count sport-based explosive actions in female athletes.[16,17]

With the increased use of wearable technology to measure the work being performed in other sports, there is no research applying this technology in the sport of ice hockey. The purpose of this study is to compare the external and internal loads of world-class female ice hockey players in training and competition across the two playing positions in the sport, as well as to provide descriptive measures for coaches to make informed decisions regarding training volume and intensity in regard to match demands. The need for descriptive research is crucial for underpinning future work in the growing field of wearable technology in the sport of ice hockey.[18]

Methods

Subjects

Twenty-five world-class female ice hockey players were included in the analysis. All 25 athletes have represented their country in international play during the 2017-2018 season. Nine of the athletes played the defense position (age 25.0 ± 3.8 y, height 170.5 ± 4.0 cm, weight 71.1 ± 8.3 kg) and 16 played forward (age 24.7 ± 3.4 y, height 172.1 ± 4.0 cm, weight 71.1 ± 4.8 kg). This study was granted ethics exemption by the York University Office of Research Ethics on the basis that it consisted of secondary analysis of existing data and did not contain any identifying information.

Design

This study used a retrospective, secondary data analysis, with on-ice metrics for all 25 athletes collected during National Team training and competitions during the 2017-2018 season. The total number of training events for the season was 61 and the total number of competition events was 44. On average, the number of training sessions participated in for defense was 48.9 ± 11.3 and 49.3 ± 10.1 for forwards. Defensive players participated in an average of 37.1 ± 8.3 competitions during the season, and forwards participated in an average of 37.1 ± 8.3 competition sessions. Athletes would not have participated in a training session due to injury, illness, or personal leave. Athletes not participating in competition based on injury, illness, personal leave, or coach decision. During training sessions, data were recorded for the duration of each drill, and edited to exclude any non-drill-based portions of the session, which included coach-talk, drill teaching, or hydration breaks. During competitions, data were recorded for the duration of each period, and edited to exclude the time between periods.

Methodology

Athletes wore a trunk-mounted Catapult S5 unit (Catapult Sports, Melbourne, Australia; firmware version 7.27) in a monitor-specific vest worn tight against the body in compliance with the manufacturer's guidelines. The integration of 100-Hz triaxial accelerometry (quantifies linear motion in all directions – acceleration and deceleration) with triaxial 100-Hz gyroscopes (sampled at 2000° per second to measure body angular motion and rotation) and 100-Hz triaxial magnetometers (measures direction and orientation of body position) allowed for the quantification of PlayerLoad during indoor activity.[8,13] The triaxial gyroscope and magnetometer functions are necessary in the aggregation of data from each specific axis in the mediolateral, vertical, and anteroposterior planes of motion to quantify PlayerLoad during dynamic multi-plane body movement.[13] Athletes also wore chest-strapped HR monitors (Polar H7, Polar Electro Oy, Finland), which recorded at 1-second intervals. Data from the Catapult S5 units and Polar H7 units were downloaded to a database maintained by the National Sports Organization. Catapult OpenField software (OpenField 1.17.0 Catapult Sports, Melbourne, Australia) was used for proprietary postprocessing of both the Catapult and Polar data.

The external load and intensity measures used in the analysis were:

PlayerLoad – A summation of all force across all movements, divided by 100.[19] This was expressed as total load (arbitrary units [au]). It is calculated as:

$$\text{PlayerLoad} = \sqrt{\frac{(a_{y1} - a_{y-1})2 + (a_x - a_{x-1})2 + (a_z - a_{z-1})2}{100}}$$

Where:

a_y = Anteriorposterior accelerometer

a_x = Mediolateral accelerometer

a_z = Vertical accelerometer

PlayerLoad·minute^{-1}– an intensity metric that looks at the rate of accumulation of PlayerLoad. It was calculated by taking the PlayerLoad value and dividing it by total duration of the activity. This has been shown to be a valid measure of intensity in Australian rules football.[20]

Explosive Efforts – a frequency count of how many explosive movements were performed. High intensity movements included: rapid accelerations and decelerations, high intensity skating, rapid changes of direction (skating-based or body contact), and high intensity shots. This count was derived from IMA data. For an event to be recorded as an explosive effort, a polynomial least squares fit was applied to the X, Y, Z resultant acceleration data and smoothed at a known frequency. This smoothed trace was overlaid with the original acceleration trace and the start and end point of the event was identified. Once identified, the sum of the X, Y area was calculated and expressed as the event magnitude (m·s^{-1}).[21] Any identified movement that occurred at a rate greater than 2 m·s^{-1} in any direction was counted. The use of IMA data, outside of being able to identify explosive actions, has not been accurately quantified or validated, therefore in keeping with best practice, IMA data was selected as a count of explosive efforts.

The internal load measure used in the analysis was:

Training Impulse (TRIMP) – using Edwards TRIMP, recorded the cardiovascular demand of the session.[22] Edwards TRIMP uses a weighting factor that is multiplied by the time accumulated in a certain HR zone (50-59% = 1, 60-69% = 2, 70-79% = 3, 80-89% = 4, 90-100% = 5). Maximum HR values were recorded during a pre-season incremental test performed on a cycle ergometer. Values were subsequently updated if the testing values were exceeded during training or competition. TRIMP was expressed as total load (arbitrary units [au]).

Statistical Analysis

A database of identified metrics for every player in each training and competitive session was created in Excel (Microsoft Corp, Redmond, WA, USA). A normal distribution of data was confirmed via the Shapiro-Wilkes test and homogeneity of variance was confirmed with Levene's test, which allowed for the use of parametric methods of analysis. Independent sample t-tests were performed to show the difference between defense and forward during training and competition sessions. Paired-sample t-tests were performed to examine the difference between training and competition for each position. Differences between positions as well as training and competition within each position were also analyzed using effect-size (ES) statistics. Effect Sizes were categorized using the following descriptors: <0.2 – trivial, 02.-0.6 – small, >0.6-1.2 – moderate, >1.2-2.0 – large, >2.0 – very large. [23] All data were processed in RStudio (version 1.0.153, R Core Team, Austria).

Results

Descriptive statistics (mean ± standard deviation) for the external and internal load and intensity measures between positions are shown in Table 1. Differences in external and internal load and intensity measures between and within positions are presented in Table 2.

***INSERT TABLE 1 ABOUT HERE ***

***INSERT TABLE 2 ABOUT HERE ***

In training sessions, forwards had higher PlayerLoad ($p < .001$, ES= 0.32), PlayerLoad·min^{-1} ($p < .001$, ES = 0.55), Explosive Efforts ($p < .001$, ES = 0.63), and TRIMP ($p < .001$, ES = 0.48). During competition, forwards also had higher PlayerLoad ($p < .001$, ES = 0.26), PlayerLoad·min^{-1} ($p < .001$, ES = 0.38), Explosive Efforts ($p < .001$, ES = 0.64), and TRIMP ($p < .001$, ES = 1.47).

When positions were viewed independently, there were several differences identified between training and competition for both forwards and defense. For defensive positions, differences were evident for PlayerLoad ($p < .001$, ES = 2.98), PlayerLoad·min^{-1} ($p = .016$, ES = 0.25), Explosive Efforts ($p < .001$, ES = 2.52), and TRIMP ($p < .001$, ES = 2.14). Similar findings were found in forwards, whereby differences were found for PlayerLoad ($p < .001$, ES = 2.63), Explosive Efforts ($p < .001$, ES = 2.08), and TRIMP ($p < .001$, ES = 1.59). There was no significant difference found for forwards between training and competition for PlayerLoad·min^{-1} (p = .641, ES = 0.0). These results suggest that across measures of on-ice external and internal loads, the volume and intensity exhibited during competition is much greater than those measured during training. These differences can be seen in Figures 1 and 2.

*** INSERT FIGURE 1 ABOUT HERE ***

*** INSERT FIGURE 2 ABOUT HERE ***

Discussion

To the authors' knowledge, this study is the first to quantify on-ice movements in world-class ice hockey using accelerometers. The first major finding from this investigation was that there are differences in both external and internal load measures between training and competition for the playing positions. Forwards had both higher volumes and intensities of load measures than defense in both training and competition. These findings are consistent with TMA-based observations, which found that defensive players had greater amounts of time in stationary positions than forwards and skated at a lower intensity for longer periods of time during competition.[3] The higher PlayerLoad and PlayerLoad·min^{-1} values for forwards could be attributed to the fact that forwards have a higher mean skating velocity compared to defense and forwards tend to skate at a higher intensity for a longer duration.[3,24] This difference could be due to tactics of play, as many teams employ an aggressive forecheck-style, which requires the forwards to skate harder at their opponent and increase the pace of play in all three zones of the ice. In this study, forwards had a greater number of explosive efforts in both training and competition, which could be attributed to style and positional pace of play. As most of the previous work regarding workload during training and games has been derived from TMA, this study has provided objective measures of on-ice work.

Similar to the results regarding external load measures, forwards exhibited higher levels of internal load. Previous literature on HR-derived information in ice hockey is mixed. Some studies have found that there is no difference between forwards and defense when measuring mean HR.[3,4] Conversely, in female ice hockey players, Spiering and colleagues[25] found that competition HRs were much higher than those measured in training, however they also reported no difference in average or peak HR between positions. This is supported by more recent work with semi-elite female ice hockey players that found that there was no difference in peak or mean HR between forwards and defense.[3] It should be noted that previous literature has focused on mean and peak HR values instead of a cumulative load measure such as TRIMP. The current study chose to measure TRIMP as it has been shown to be a reliable measure of both intensity and internal training load in previously published work with team-based load monitoring.[26–28]

In both positions, data for external and internal loads were different based on the type of session. In all cases, training session loads and intensities were lower than competition sessions. The higher competition loads could be attributed to the more competitive and physical nature of match-play, along with the higher pace associated with competition. The amount and duration of coaching at training could account for the lower intensity and workload of these sessions. Periods of instruction and skill work, with a focus on technical and tactical improvement are often prevalent in training sessions, which would have a lower intensity than competitive periods of play. It is suggested that coaches aiming to replicate competition demands include competitive-based drills or small-sided games during training sessions.[19]

The measuring of positional characteristics in training and competition, while novel in ice hockey, is well-established in other sports. For example, similar differences between positions in regard to external load has been shown in Australian Football, where PlayerLoad varied across the different positions.[19] Comparable findings regarding the disparity between training and competition loads have been reported in international rugby sevens as well. Relative to competition, training data were shown to be lower in intensity (maximal velocities, impacts, accelerations and decelerations, mean HR, peak HR, and TRIMP) and volume (total distance covered).[29] Gabbett replicated the examination in elite female field hockey players with similar results, concluding that athletes had decreased volumes and intensities in training compared to competition and that training sessions were a poor reflection of the physiological demands of competition.[30]

The current study is novel in terms of the sport (ice hockey), participant group/gender (world-class female players), and technology used (accelerometers), however it also has some limitations. Direct comparisons with previously published accelerometer-derived data were not possible due to the paucity of literature in high-level female ice hockey players. Athletes wore the same unit every session, while consistent, can introduce bias as accelerometers have been found to show poor interunit reliability.[15] Another limitation is that there was no correction for the natural fluctuation of volume and intensity based off weekly schedules. All the training sessions were included in the data set, without identifying high load or low load days. Further research can investigate the periodization of planning that occurs during an ice hockey season. Future work investigating internal load using TRIMP should focus on using a modified TRIMP, which has been shown to provide a measure of internal load during team sports of a high-intensity and intermittent nature. The use of modified TRIMP in intermittent, high intensity sport has merit as it applies a different weighting factor for each HR zone that resembles a typical blood lactate response curve, thus the duration of work performed at higher HR zones can be exponentially weighted.[28] The inclusion of high-level athletes, while a unique data set, might limit the generalizability to other populations. There is a paucity of research in the application of wearable technology to monitor both external and internal load in ice hockey, as the body of research grows it will be important to begin to understand the unique movement patterns and movements strategies that are inherent to ice hockey, such as the impact of low-intensity locomotion or gliding and its relationship to external and internal loads. As this is the only investigation to date assessing accelerometers in ice hockey training and competition, further investigation is required to develop a greater understanding of the role these devices can play in improving player performance.

Practical Application

The results of the present study demonstrate that wearable technology, in the form of accelerometers and HR monitors, provide valuable information regarding the on-ice volumes and intensities of both training and competition in ice hockey. This information can be used by coaches to further improve their training sessions and closely mirror competition demands. The information collected from wearable technology quantifies athletic performance and allows coaches to make informed decisions. Coaches could benefit from spending time working the positions separately and use the information contained within to better prepare athletes for the demands of competition. This information can be used to prescribe position-specific training approaches to further enhance the training process. Furthermore, the differences between positions are important as coaches need to plan training that reflects adequate work volume and intensity for both positions to help mitigate undertraining in relation to competitive demands.

Conclusion

Specificity of training is an important consideration for the prescription of physical performance programs to elicit physiological adaptations to improve competitive performance. Understanding the differences between positions, as well as training and competition demands can further refine the athlete preparation process. The use of wearable technology in elite sports is growing, as such ice hockey is a sport to which the information collected from these units can provide objective data regarding the on-ice demands. There are clear differences in the volume and intensity of external and internal workloads between training and competition sessions, with athletes experiencing much less across all measures in training sessions. Understanding the demands of competition facilitates the modification of training drills to improve specificity and adopt position-specific training approaches. Similarly, these differences were also evident when comparing the skating positions, with defense having lower loads and intensities compared to forwards. We conclude that there are markedly different volume and intensity outputs between training and competition, and this information will allow coaches and athletes to design improved training sessions to increase their complexity and intensity to better simulate the demands of competition. Monitoring the external and internal competition loads provides coaches a quantified approach to ensure that training demands are high enough to optimally prepare players for the demands of competition.

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APPENDIX B: ACCEPTED MANUSCRIPT IN JOURNAL FORMAT (*SPORTS*)

Article

On-Ice Measures of External Load in Relation to Match Outcome in Elite Female Ice Hockey

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Abstract: The aim of this study is to investigate the differences between select on-ice measures using inertial movement sensors based on match outcome, and to determine changes in player movements across three periods of play. Data were collected during one season of competition in elite female ice hockey players (N = 20). Two-factor mixed effects ANOVAs for each skating position were performed to investigate the differences in match outcome, as well as differences in external load measures during the course of a match. For match outcome, there was a small difference for forwards in explosive ratio (p = 0.02, ES = 0.26) and percentage high force strides (p = 0.04, ES = 0.50). When viewed across three periods of a match, moderate differences were found in skating load (p = 0.01, ES = 0.75), explosive efforts (p = 0.04, ES = 0.63), and explosive ratio (p = 0.002, ES = 0.87) for forwards, and in PlayerLoad (p = 0.01, ES = 0.70), explosive efforts (p = 0.04, ES = 0.63), and explosive ratio (p = 0.01, ES = 0.70) for defense. When examining the relevance to match outcome, external load measures associated with intensity appear to be an important factor among forwards. These results may be helpful for coaches and sport scientists when making decisions pertaining to training and competition strategies.

Keywords: monitoring; PlayerLoad; skating load; explosive efforts; explosive ratio; percentage of high force strides

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1. Introduction

Ice hockey is a major international sport with over one million registered participants across the globe [1]. For optimal performance, ice hockey athletes require well-rounded physical and physiological capabilities (amongst other qualities), including high aerobic and anaerobic capabilities, muscular strength, power, and endurance [2]. These physiological qualities are expressed in ice hockey by combining dynamic skating movement patterns with skills such as skating, shooting, and passing of the puck [1].

The incorporation of evidence-based approaches into training has become a critical component in many competitive sports, including ice hockey. This movement is reflected in the integration of sport science experts (analysts, medical teams, and researchers), as well as in an increased use of technology to help increase scientific rigor [3,4]. Specifically, the inclusion of wearable technologies (also known as 'wearables'), such as heart rate monitors, global positioning systems (GPS), and accelerometers, has become common in many elite sport programs. In 2016, wearables (both consumer-based and athlete-based) were estimated to be a six-billion-dollar industry [5]. It is believed that the use of wearables may enhance coaches' decision-making practices, while also helping to optimize player performance [6]. Specifically, training interventions, tactical assessments, competition preparation, and athlete feedback are just some of the areas influenced by the incorporation of wearable technologies in sport programs [7–9]. It is the hope that collecting and analyzing data from wearables, along with appropriately interpreting and applying the findings, can improve consistency of performance outcomes and the prevention of excess fatigue and overuse injuries [10]. The prevailing method to measure work performed on the ice in hockey research is through time-motion analysis (TMA). TMA has been widely used across many team sports [11–13], but is often criticized when applied to sports where player movements are extremely explosive and short in duration, and therefore difficult to record accurately [1].

The inclusion of wearables that measure external load variables in competitive sport programming may be an avenue for coaches and sport medicine practitioners, researchers, and strength and conditioning coaches to meaningfully track athletes' performance in a way that extends beyond internal load methods—like subjective perceived ratings of exertion and heart rate measurement. External load refers to the interaction of volume and intensity that athletes experience during their sport, and often refers to the work performed by an athlete [14]. Typically, the quantification of this 'work' (i.e., movement demands) is captured through GPS, accelerometers, and/or video analysis. To date, the precision, reliability, and accessibility of GPS and accelerometers continue to improve, which has allowed sport science practitioners to use them at the highest levels of sport. For example, in 2015, the Federation Internationale de Football Association (FIFA) for men's and women's soccer allowed the collection of data during competitive matches using GPS [8]. Similarly, elite rugby league players wore GPS to capture physical demands during competitive matches [15]. Despite its prevalence in other team sports, the adoption of wearables by key decision-makers in ice hockey, including managers, coaches, and players, has been less immediate. This may be related to the limited empirical research on the degree of transferability between playing surfaces (i.e., ground compared to ice). Additionally, there are other administrative, financial, and logistical constraints that likely play a role in this slow uptake and implementation in the sport of ice hockey.

In the evolving climate of sport, the question of which statistics should be used has become a more important question than whether statistics should be used when it comes to many facets of decision-making. In the context of wearables, selecting which metrics to use has become a critical question. The value lies in the determination and prioritization of the key metrics for each sport that yield the most information, value, validity, reliability, and predictive capabilities. For example, Gabbett highlighted that valuable information was gleaned by comparing match data from wins and losses in team sports [15]. Specifically, the physical demands in elite rugby, measured using GPS and accelerometers, were higher when the team was winning versus losing, and when competing against lower ranked teams [15]. Although this study focused on rugby, the findings suggest that success in matches is linked to the team's ability to maintain a higher playing intensity and may also be applicable to the sport of ice hockey. Similar findings in other team sports support the notion that player output varies depending on the result of the match. In soccer, it has been shown that high-intensity activity by key positions had a positive impact on winning [16,17]. The timing of these high-intensity events in soccer has also been shown to have a relationship with winning, as teams who display higher peak and mean running speeds in the second half of the game have a greater likelihood of winning the match [18].

Findings such as these could have direct implications for practice and competition strategies. Even slight changes to tactical strategies, athlete workload, and performance outputs may play a vital role in the outcome of a competition (e.g., shift changes and in-game strategies). Match outcome and its relationship to physical and tactical performance has been widely studied in other team sports [14,17,18–22], allowing coaches and sport scientists to prepare more effective training and competition strategies to have a positive impact on performance outcome. The application of wearable technology in elite ice hockey is an area of potential growth in sport science, with recent work exploring the difference between external and internal metrics between training and competition. Differences were evident when comparing data between playing positions, with defense having lower outputs of PlayerLoad, PlayerLoad·min^{-1}, Training Impulse (TRIMP), and explosive efforts compared to forwards [23]. For the sport of ice hockey, there remains a void in the literature examining the playing conditions for elite level teams. The integration of player tracking technology at all levels of the sport has the potential to modernize the landscape of hockey analytics. Specifically, the inter- and intra-player and positional differences within and between competitive matches appear to be under-represented in the literature. Therefore, the primary aim of this study is to examine differences captured by wearable technology through inertial movement sensors worn by athletes in ice hockey matches. The hypothesis is twofold; higher player movement and intensity plays a role in match outcome, as well as player movement and intensity decrease across the game.

2. Materials and Methods

2.1. Study Design

A mixed effects design was employed to investigate the differences in on-ice measures of external load during competition, and whether these measures differed based on the outcome of the game (i.e., win or loss) by period of play, and the interaction of match outcome and period. This study used a retrospective, secondary data analysis with on-ice metrics for all 20 athletes collected during Hockey Canada's Senior National Women's Team matches during the 2016–2017 season. The team participated in 26 matches, with an outcome of 13 wins and 13 losses. Data were averaged for each position and reported for all three periods of play to allow for a repeated measures design comparing the differences specifically between match periods.

2.2. Participants

Elite female ice-hockey players (age = 24.8 ± 3.5 years; height = 171.6 ± 6.1 cm; body mass = 71.1 ± 6.1 kg) who represented their country in exhibition and international matches participated in this study. Using Baker and colleague's taxonomy [24], this sample of athletes would be considered 'expert' based on their highest level of competition at the international level. The sample consisted of 13 forwards and seven defensive players. Goalies were excluded from the analysis due to their unique movement characteristics. All subjects gave their written informed consent for inclusion before they participated in the study. The study was conducted in accordance with the Declaration of Helsinki and was granted ethics exemption by the York University Office of Research Ethics on the basis that it consisted of secondary analysis of existing data and did not contain any identifying information.

2.3. Procedure

Each athlete wore a trunk-mounted (strapped to chest) Catapult S5 unit (Catapult Sports, Melbourne, Australia; firmware version 7.27) in a monitor-specific vest worn tight against the body in compliance with the manufacturer's guidelines. The integration of 100-Hz triaxial accelerometry (quantifies linear motion in all directions—acceleration and deceleration) with triaxial 100-Hz gyroscopes (sampled at 2000° per second to measure body angular motion and rotation) and 100-Hz triaxial magnetometers (measures direction and orientation of body position) allowed for the quantification of PlayerLoad during indoor activity [25,26]. The triaxial gyroscope and magnetometer functions are necessary in the aggregation of data from each specific axis in the mediolateral, vertical, and anteroposterior planes of motion to quantify PlayerLoad during dynamic multi-plane body movement [26]. Data from the Catapult S5 units were downloaded to a database maintained by the National Sports Organization. Catapult OpenField software (OpenField 1.17.0 Catapult Sports, Melbourne, Australia) was used for proprietary postprocessing. Previous studies have reported the Catapult Sports S5 to have an excellent intradevice reliability for

PlayerLoad values, with most Coefficient of Variation (CV) values rating low (<1.0%) [26,27]. It has also been reported that Intraclass Correlation Coefficient (ICC) ranged from 0.8 to 1.0 for intradevice comparison [27].

2.4. External Load Metrics

A description of the metrics used in the analysis are:

PlayerLoad is the summation of accelerations across all movements, divided by 100 [27]. This was expressed as total load (arbitrary units (au)). It is calculated as:

$$\text{PlayerLoad} = \sqrt{\frac{(a_{y1} - a_{y-1})^2 + (a_x - a_{x-1})^2 + (a_z - a_{z-1})^2}{100}} \quad (1)$$

where: a_y = Anteriorposterior acceleration; a_x = Mediolateral acceleration; a_z = Vertical acceleration.

Skating load is the summation of all peak accelerations recorded during the skating stride. Skating load is derived from a proprietary algorithm to identify the hockey stride based off the accelerometer tracing, gyroscope, and magnetometer sensors. The corresponding resultant acceleration peaks are calculated and multiplied by the athlete's mass. This was expressed as total load (arbitrary units (au)). It is calculated as:

$$\text{Skating Load} = (\sqrt{(a_y)^2 + (a_x)^2 + (a_z)^2} \times \text{Player Mass})/100 \quad (2)$$

Explosive efforts is the frequency of how many explosive movements were performed. High-intensity movements included: Rapid accelerations and decelerations, high-intensity skating, rapid changes of direction (skating-based or body contact), and high-intensity shots made by the player. This count was derived from Inertial Movement Analysis (IMA) data. Once identified, the sum of the X, Y area was calculated and expressed as the event magnitude ($m \cdot s^{-1}$) [28]. Any identified movement that occurred at a rate greater than 2 $m \cdot s^{-1}$ in any direction was considered an explosive effort [23].

Explosive ratio is a ratio calculated by taking the total number of explosive efforts and dividing it by PlayerLoad. This provides information as to the athletes' ability to produce explosive movements based off their total load accumulation throughout the course of a match.

Percentage high force strides captures the percentage of all the ice hockey strides that occurred in the high force band. For female ice hockey players, strides that exceed 140 au skating load are coded as high force strides based off banding recommendations from the manufacturer.

2.5. Statistical Analysis

For each variable listed above, a two-factor mixed effects ANOVA was performed to investigate the difference in matches that were won and lost, as well as the difference in variables across the three periods of play. A normal distribution of data was examined using the Shapiro-Wilk's test and homogeneity of variance was confirmed with Levene's test, which supported the use of parametric methods of analysis. Due to the differences in match demands, forwards and defensive players were analyzed separately. All data were processed in RStudio (version 1.0.153, R Core Team, Vienna, Austria). Differences between match outcome as well as between periods were analyzed using effect size (ES) statistics. To ensure consistency in reporting of results and comparability across all analyses, the partial eta-squared statistics from ANOVA were also converted to ES [29]. Effect sizes were categorized using the following descriptors: <0.2—trivial, 0.2–0.6—small, >0.6–1.2—moderate, >1.2–2.0—large, >2.0—very large [30]. Data are presented as mean ± SD and statistical significance was set at $p \leq 0.05$.

3. Results

3.1. Descriptive Summary of On-Ice Metrics and Two-Way ANOVA Results

The descriptive statistics for the different metrics are summarized in Table 1 for forwards and Table 2 for defense. The results of the two-way mixed effect ANOVAs can be found in Table 3 for forwards and Table 4 for defense.

Table 1. Descriptive statistics of select external load variables for forwards, by game outcome and period.

Select External Load Variable—Forwards			Mean	SD
PlayerLoad	Win	First Period	692.82	104.65
		Second Period	674.30	92.97
		Third Period	667.37	112.58
	Loss	First Period	716.04	112.00
		Second Period	659.79	134.08
		Third Period	714.52	139.19
Skating Load	Win	First Period	527.24	20.39
		Second Period	493.04	39.50
		Third Period	484.94	37.97
	Loss	First Period	517.88	26.57
		Second Period	467.11	67.58
		Third Period	498.78	80.97
Explosive Efforts	Win	First Period	1043.31	143.74
		Second Period	968.92	133.20
		Third Period	945.62	138.93
	Loss	First Period	1045.54	118.49
		Second Period	907.08	185.36
		Third Period	981.46	194.42
Explosive Ratio	Win	First Period	1.51	0.10
		Second Period	1.44	0.09
		Third Period	1.43	0.11
	Loss	First Period	1.47	0.10
		Second Period	1.38	0.07
		Third Period	1.37	0.13
Percentage High Force Strides	Win	First Period	17.70	1.21
		Second Period	17.11	1.24
		Third Period	17.00	1.43
	Loss	First Period	16.41	1.78
		Second Period	16.25	1.99
		Third Period	16.78	2.26

Table 2. Descriptive statistics of select external load variables for defense, by game outcome and period.

Select External Load Variable—Defense			Mean	SD
PlayerLoad	Win	First Period	363.19	60.04
		Second Period	358.43	58.29
		Third Period	346.64	65.55
	Loss	First Period	371.37	54.99
		Second Period	346.59	50.51
		Third Period	354.61	65.96
Skating Load	Win	First Period	477.76	48.48
		Second Period	453.19	52.43

		Third Period	434.41	49.62
	Loss	First Period	484.66	59.74
		Second Period	453.41	82.51
		Third Period	445.38	98.04
Explosive Efforts	Win	First Period	478.23	77.25
		Second Period	449.31	87.78
		Third Period	421.38	88.47
	Loss	First Period	486.92	53.47
		Second Period	438.77	58.53
		Third Period	429.38	103.46
Explosive Ratio	Win	First Period	1.32	0.11
		Second Period	1.25	0.13
		Third Period	1.21	0.13
	Loss	First Period	1.32	0.13
		Second Period	1.27	0.09
		Third Period	1.21	0.19
Percentage High Force Strides	Win	First Period	10.20	2.00
		Second Period	10.21	2.41
		Third Period	9.93	1.99
	Loss	First Period	10.45	2.40
		Second Period	10.55	2.39
		Third Period	10.49	2.44

Table 3. Two-way ANOVA results of select external load variables on game outcomes and periods for forwards.

Select External Load Variables—Forwards		F-Statistic	*p*	ES
PlayerLoad	WinLoss	F(1,72) = 0.48	0.48	0.20
	Period	F(2,72) = 0.51	0.51	0.29
	WinLoss:Period	F(2,72) = 0.63	0.63	0.20
Skating Load	WinLoss	F(1,72) = 0.39	0.53	0.20
	Period	**F(2,72) = 4.92**	**0.01**	**0.75**
	WinLoss:Period	F(2,72) = 1.02	0.37	0.35
Explosive Efforts	WinLoss	F(1,72) = 0.05	0.82	0.06
	Period	**F(2,72) = 3.35**	**0.04**	**0.63**
	WinLoss:Period	F(2,72) = 0.68	0.52	0.29
Explosive Ratio	**WinLoss**	**F(1,72) = 5.30**	**0.02**	**0.26**
	Period	**F(2,72) = 6.63**	**0.002**	**0.87**
	WinLoss:Period	F(2,72) = 0.10	0.91	0.02
Percentage High Force Strides	**WinLoss**	**F(1,72) = 4.21**	**0.04**	**0.50**
	Period	F(2.72) = 0.33	0.72	0.20
	WinLoss:Period	F(2,72) = 0.65	0.52	0.29

Note: Bold font indicates $p < 0.05$.

Table 4. Two-way ANOVA results of select external load variables on game outcomes and periods for defense.

Select External Load Variables—Defense		F-Statistic	*p*	ES
PlayerLoad	WinLoss	F(1,72) = 0.02	0.89	0.06
	Period	**F(2,72) = 4.51**	**0.01**	**0.70**
	WinLoss:Period	F(2,72) = 0.08	0.92	0.09
Skating Load	WinLoss	F(1,72) = 0.15	0.69	0.09
	Period	F(2,72) = 2.52	0.08	0.50

	WinLoss:Period	F(2,72) = 0.04	0.96	0.06
Explosive Efforts	WinLoss	F(1,72) = 0.01	0.91	0.06
	Period	**F(2,72) = 3.45**	**0.04**	**0.63**
	WinLoss:Period	F(2,72) = 0.12	0.89	0.11
Explosive Ratio	WinLoss	F(1,72) = 0.02	0.89	0.06
	Period	**F(2,72) = 4.51**	**0.01**	**0.70**
	WinLoss:Period	F(2,72) = 0.08	0.92	0.09
Percentage High Force Strides	WinLoss	F(1,72) = 0.55	0.46	0.20
	Period	F(2.72) = 0.04	0.96	0.06
	WinLoss:Period	F(2,72) = 0.03	0.97	0.06

Note: Bold font indicates $p < 0.05$.

3.2. PlayerLoad

For the defensive players, there was no statistically significant difference between wins and losses, however, a statistically significant difference was found between periods (F(2,72) = 4.51, p = 0.01, ES = 0.70), with the first period having the highest PlayerLoad (482.58 ± 65.24), followed by the second period (444.04 ± 73.29) and third period (425.38 ± 94.40). Post hoc testing using Tukey HSD indicated there was a moderate decrease from the first period to third period (p = 0.01, ES = 0.70).

3.3. Skating Load

For forwards, a two-way ANOVA identified a statistically significant difference for skating load between periods (F(2,72) = 4.92, p = 0.01, ES = 0.75), with the first period having the highest load (522.56 ± 23.70), followed by the third period (491.86 ± 62.36), with the second period demonstrating the lowest load (480.1 ± 55.82). Post hoc testing using Tukey HSD indicated a moderate decrease from the first to second period (p = 0.01, ES = 0.98).

3.4. Explosive Efforts

There was a statistically significant difference for explosive efforts between periods for the forwards (F(2,72) = 3.35, p = 0.04, ES = 0.63), with the first period having the highest rating (1044.42 ± 129.06), followed by the third period (963.54 ± 161.25), and second period (938.00 ± 161.25). Post hoc testing using Tukey HSD indicated that there was a moderate decrease from the first period to second period (p = 0.04, ES = 0.73).

For defensive players, a statistically significant difference between periods was also found (F(2,72) = 3.45, p = 0.04, ES = 0.63), with the first period reporting the highest explosive efforts (482.58 ± 65.24), followed by the second period (444.04 ± 73.29) and the third (425.28 ± 94.40). Post hoc testing using Tukey HSD showed there was a moderate decrease between the first period and third period (p = 0.03, ES = 0.71).

3.5. Explosive Ratio

For forwards, there was a main effect of match outcome (F(1,72) = 5.30, p = 0.02, ES = 0.26), such that the average explosive ratio in matches that were won were higher (1.46 ± 0.10) than lost (1.41 ± 0.11). There was a statistically significant difference between periods (F(2,72) = 6.63, p = 0.002, ES = 0.87), with the first period demonstrating the highest explosive ratio (1.49 ± 0.10), followed by the second (1.41 ± 0.09) and the third (1.40 ± 0.12). Post hoc testing using Tukey HSD indicated a moderate decrease from the first period to both the second (p = 0.01, ES = 0.84) and third periods (p = 0.004, ES = 0.81).

For defensive players, there was a main effect of period number (F(2,72) = 4.51, p = 0.01, ES = 0.70), whereby the first period reported the highest explosive ratio (1.32 ± 0.12), followed by the second (1.26 ± 0.11) and third (1.21 ± 0.16). Post hoc testing using Tukey HSD showed a moderate decrease between the first period and third period (p = 0.01, ES = 0.78).

3.6. Percentage High Force Strides

The forward group showed a statistically significant difference between match outcome ($F(1,72) = 4.21$, $p = 0.04$, ES = 0.51), where a higher percentage of high force strides were found in matches that were won (17.27 ± 1.30) compared to matches that were lost (16.48 ± 1.98).

4. Discussion

In this study, we report data from wearable technology using selected metrics of external load collected during matches, and their differences based on match outcomes across three periods of play. Our results generally support the use of wearable technology for collecting player data related to volume and intensity, as measured through various metrics of external load. When examining the relevance to match outcome, indices of external load appears to be an important factor in this sample of elite female ice hockey players, but only among the forwards where a significant difference for explosive ratio and the percentage of high force strides was found in matches that were won versus lost. Both are indicators of on-ice skating intensity, suggesting that the ability to have a high output of skating intensity is important for success in matches.

The results also demonstrate a significant drop in external load measures from the first period to the second period. The second period had lower measured skating load and explosive efforts compared to the first and third period. With the sport of ice hockey being broken up into three 20-min periods interspersed with a 15-min intermission, one could surmise that the drop-off would be similar across the later periods due to the intermission, which affords the athletes the ability to rest and recover. Evidence of this declining output was seen in the defensive group, where significant differences in period output was found in PlayerLoad, explosive efforts, and explosive ratio. In all three of these variables, the first period had the highest output and the third period the lowest, which might be attributed to the accumulation of fatigue. The recent work by Lignell and colleagues [31] in men's ice hockey using video-based external load monitoring supports evidence of declining outputs because of fatigue. The researchers showed that the average sprint-skating speed was lower in the later periods of the match. There may be several explanations as to why this occurs in ice hockey. One reason could be the inability to repeat the appropriate number of high-speed bouts within a hockey match. It has been shown in ice hockey players that a high aerobic power increases the ability to recover from repeated bouts of anaerobic power [32]. Peterson and colleagues found a high correlation between maximal oxygen uptake and fatigue during the later periods of a mock hockey match in high-level collegiate hockey players [33]. Another explanation could be attributed to the tactical situation of the match during the later phases of competition. If a team is winning, the team may adjust their strategy to play more conservatively, which could alter player output, unrelated to fitness or fatigue. In most high-level ice hockey, coaches prefer to play an assertive style forecheck when the score is close to attack the opponent and increase the pace of play. This up-tempo style relies on a fast-skating aggressive style of forecheck most coaches employ from a tactical perspective [34].

Another interesting finding from on-ice tracking data of men's professional ice hockey reported players performed an average of seven high-intensity skating bouts every minute [31], which is proportionally much higher than reported in other field and court-based team sports [35–37]. According to the published TMA literature for female ice hockey, forwards had an average of 18 forward shifts per match, with a mean duration of 48 s; whilst their defensive teammates averaged 15 defensive shifts per match with an average shift duration of 43 s. Each shift consisted mainly of low- to moderate-intensity skating interspersed with brief, intermittent high-intensity bouts [11].

Additionally, other studies have assessed the physiological demands of ice hockey during competition. In conjunction with aerobic training, it has also been shown that a positive relationship exists between ice hockey players with higher anaerobic power scores and their draft position in the National Hockey League [38]. Both are related to the outputs required for individual on-ice success, (i.e., the ability to produce high-intensity output and to repeat the high-intensity bouts). The finding that positional differences relate to match outcome did not come as a surprise, as it has been reported that the match demands placed on forwards and defense are vastly different [23]. Female ice hockey forwards have been found to have greater anaerobic power output, as well as a higher aerobic capacity, when compared to female ice hockey defensive players [39], along with a higher duration and frequency of high-intensity skating than defensive players [11]. These differences are most likely attributed to the different positional demands, whereby the defensive group retreats more often and typically covers a lower proportion of the ice. Positional differences were also reflected in men's professional ice hockey, with forwards exhibiting a higher average skating speed and covering a greater distance at high-intensity [31]. Taken together, it appears that for success in ice hockey, it is important for players to be able to tolerate high-intensity and high-velocity efforts, as well as the ability to endure repeat anaerobic bouts. This can have important implications for coaches and sport medicine practitioners alike to help inform periodized training and competition practices, especially as it relates to match outcomes.

To the authors' knowledge, this is the first study of its kind to examine wearable technology during competitive matches in the sport of women's ice hockey. Some studies have examined the physiological demands in relation to team success in ice hockey [40], however, this study is unique in that multiple performance metrics were assessed via wearable technology (PlayerLoad, skating load, explosive efforts, explosive ratio, and percentage high force strides). While our study is novel in terms of using measurable match data from accelerometers to uncover determinants of match play and match outcome, there are certain limitations that are important to acknowledge. The first is the length of time the data were collected. Increasing the study length to include multiple seasons with the same athlete sample and coaching staff could allow for patterns to emerge, both from the main effects and the interactions between winning and losing and player metrics during different periods of the game. A second limitation is that due to the variable nature of player deployment in ice hockey, large standard deviations were present. Player ice time is largely dictated by coaching strategy, and thus using a positional average dataset can be limiting. Further research could focus on the higher-performing players (e.g., top six forwards and top four defense). Furthermore, while the inclusion of high-level athletes allowed for a unique and valuable data set, it limits the generalizability of our results to other populations, such as a non-expert group of ice hockey players, which would allow researchers to track changes between levels of performance.

5. Conclusions

The results of the present study demonstrate the potential benefits of using wearable technology to collect data on performance metrics in the sport of ice hockey. With appropriate assessment and implementation, it may positively impact coaches' decision-making as it pertains to game demands and game outcome. The results suggest the intensity measure of external load of game play by forwards has an impact on match outcome. Secondary results show between-period differences for forwards with the second period typically lower in external load measures than the first period or third period. For defensive players, a difference in external load across all three periods was evident, with the main findings suggesting a drop-off between the first and third periods. There is a paucity of research in the application of wearable technology to monitor external load in ice hockey, and as the body of research grows it will be important to understand the unique movement patterns and movements strategies that are inherent to ice hockey, such as the impact of low-intensity locomotion or gliding and its relationship to skating performance. Future research could further investigate the reasons behind the decreased output across a match to determine if it is physiological fitness- or fatigue-related, as well as explore the use of some of the between-period interventions utilized by other high-performance teams in other sports.

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supervision of M.A.R. and A.K.M. Original draft preparation was undertaken by A.D. and K.J., while review and editing was undertaken by A.D., K.J., J.B., M.A.R., V.K.J., and A.K.M.

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