Heart Rate Variability as an indicator of pre-competition training effectiveness on increasing ice hockey performance.

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April 15, 2024

A thesis submitted to McGill University in partial fulfillment of the requirements of the degree of Masters of Science in Exercise Physiology.

Table of Contents

Table of Contents **2**

List of Figures 5

List of Tables 5

List of Equations 6

List of Common Terms and Abbreviations 7

Acknowledgements **8**

Abstract **9**

Preface and Authors Contributions **13**

Chapter 1 - Introduction **14**

1.1 Scope of Study 14

1.2 Rationale 16

1.3 Purpose 18

1.4 Hypotheses 18

1.5 Delimitations 19

1.6 Limitations 20

1.7 Strengths 20

Chapter 2 – Literature Review **21**

2.1 Post-Activation Performance Enhancement 21

2.2 Heart Rate Variability 32

2.3 HRV and Autonomic Nervous System Relation to Exercise and Sport 35

2.4 Omegawave Technology 43

Chapter 3 – Methods 46

3.1 Participants 46

3.2 Experimental Timeline 47

3.3 Anthropometric Measurements 49

3.4 Whole and Regional Body Composition 49

3.5 1-Repetition Maximum Estimation Test 50

3.6 On-Ice Performance Test 51

3.7 Post-Activation Performance Enhancement 52

3.8 Pre-Competition Training 52

3.9 Omegawave Test 53

3.10 Heart Rate Variability Classification 54

3.11 Statistical Analysis 54

Chapter 4 – Manuscript 57

Abstract 58

Introduction 59

Methods 61

Results 66

Discussion 71

Practical Applications 75

References 77

Tables and Figures 81

Chapter 5 – Summary, Conclusion, Recommendations, and Practical Application.............91

5.1 Summary 91

5.2 Conclusion...93

5.3 Recommendations 94

5.4 Practical Application 95

Appendix...97

References...104

List of Figures

Chapter 2

Figure 1 – Percent changes in countermovement jump performance following either a fixed or self-selected rest interval.

Chapter 3

Figure 1 – Experimental Timeline.

Chapter 4

Figure 1 – On-Ice Performance Metrics PAPE (%) for Male and Female Varsity Hockey Players.

Figure 2 – On-Ice Performance Metrics PAPE (%) for Players Classified as Having a High or Low HRV Score.

List of Tables

Chapters 3 & 4

Table 1 – Loads used by male and female participants during the 1RM estimation test.

Table 2 – Warm-up and training percentages, as well as repetitions, used during the pre-competition training session.

Chapter 4

Table 3 – Characteristics (Mean ± SEM) of Male and Female Varsity Hockey Players.

Table 4 – Measurements (Mean ± SD) of Athlete Readiness, HRV, and DC Potential at Baseline On-Ice Testing, Pre-Training, and Post-Training On-Ice Testing.

Table 5 – On-Ice Performance Metrics (Mean ± SD) at Baseline and Post-Training On-Ice Testing in Male and Female Varsity Hockey Players.

Table 6 – Changes in HRV and On-Ice Performance Metrics in Male and Female Varsity Hockey Players (Mean ± SD).

Table 7 – Number of Male and Female Hockey Players with High or Low HRV Scores.

Table 8 – Average On-Ice Performance PAPE (%) for Male and Female Varsity Hockey Players Classified as Having High or Low HRV Scores.

List of Equations

Chapters 3 & 4

Equation 1.1 – Estimated Relative Load (Percentage of 1RM).

Equation 1.2 – Estimated 1RM.

Equation 2.1 – Peak Sprint Velocity.

Equation 2.2 – Average Sprint Time.

Equation 2.3 – Average Sprint Velocity.

Equation 3 – Percentage of Post-Activation Performance Enhancement (PAPE).

List of Common Terms and Abbreviations

PAPE – Post-Activation Performance Enhancement

HRV – Heart Rate Variability

ANS – Autonomic Nervous System

SNS – Sympathetic Nervous System

PNS – Parasympathetic Nervous System

CA – Conditioning Activity

RMSSD – Root Mean Square of Successive RR Intervals

SDNN – Standard Deviation of NN Intervals

CMJ – Countermovement Jump

NHL – National Hockey League (Professional)

*Manuscripts were formatted for a particular journal; therefore, abbreviations may not have been used in these two chapters.

Acknowledgments

I would like to acknowledge many individuals for their support and contribution during the time spent completing my Master's thesis. First off, I would like to thank Dr. Ross Andersen, my graduate school supervisor, for his guidance and expertise on how to conduct research and write a Master's thesis. He dedicated much of his time to helping me complete this project.

Secondly, I would like to thank my committee members, Dr. Jordan Koch and Pat Delisle-Houde, for their feedback and knowledge on performing a proper scientific research study. Without their advice, my research would not have been as successful.

I would also like to thank the McGill Redbird and Martlet ice hockey coaches, David Urquhart and Alyssa Cecere, for their support in allowing me to include their athletes in my research. Along the same lines, I would like to acknowledge and express my gratitude to the McGill ice hockey players of the 2023-2024 season for their participation in my study.

Finally, I would like to thank my dad, Richard, my mother, Kristine, and my fiancée, Cali, for their unwavering support and encouragement these last three years. Without them, I wouldn't have been able to complete this project while working and coaching the hours I did.

To all,

Thank you very much.

Abstract

Ice hockey players are continuously looking for ways to optimize their on-ice performance during competition. Many athletes are using technology to monitor their recovery and physiological readiness through heart-rate variability (HRV) readings. This monitoring acts as a tool to gauge the effectiveness of their recovery methods and their training. Another effective means of enhancing performance is with resistance training. Resistance training on the morning of a competition provides a post-activation performance enhancing (PAPE) effect. However, the effects experienced by an athlete are highly dependent on the individual, therefore, determining whether an athlete will respond positively requires an objective means of testing. With the prior literature on HRV, its responses to training, and its relation to performance, the purpose of this study is to determine whether an ice hockey player's morning HRV is an indication of the effectiveness of pre-competition training for inducing a positive PAPE effect. A secondary purpose of the study is to explore sex differences in the responses to the pre-competition training, as well as in the relationship between HRV and PAPE.

Participants were asked to complete an on-ice performance test at baseline and on a secondary day, 4 to 6 hours following the resistance training session. The participants were categorized into two groups (High, Low) based on their HRV score before the training session. A two-factor ANOVA analysis was conducted to determine the effects of HRV classification, sex, and HRV-sex interaction on the PAPE effects seen in the different performance metrics. The athletes categorized as having a low HRV experienced a significantly ($p < 0.05$) greater decrease in average sprint time and a greater increase in average sprint velocity, but no improvement in peak sprint velocity. Female participants improved ($p < 0.05$) more than the

male participants in all performance metrics. Although both HRV classification and sex had effects on PAPE, no HRV-sex interaction effects were observed.

The findings of this study can benefit strength and conditioning coaches working with ice hockey players. By monitoring an athlete's HRV the morning of a competition, a coach may be able to objectively determine how they will respond to a pre-competition training session and whether it is beneficial to prescribe one. This information can help increase the customization and optimization of an athlete's preparation for competition.

Résumé

Les joueurs de hockey sur glace cherchent continuellement des moyens d'optimiser leurs performances sur la glace pendant leurs compétitions. De nombreux athlètes utilisent la technologie pour surveiller leur récupération et leur état de préparation physiologique grâce à la mesure de la variabilité du rythme cardiaque (VRC). Ce suivi sert d'outil pour évaluer l'efficacité de leurs méthodes de récupération et de leur entraînement. L'entraînement en résistance est un autre moyen efficace d'améliorer les performances. Plus précisément, un entraînement de résistance le matin d'une compétition produit un effet d'amélioration de la performance post-activation (PAPE). Cependant, les effets ressentis par un athlète dépendent fortement de l'individu. C'est pourquoi il est nécessaire de disposer d'un moyen de test objectif pour déterminer si un athlète réagira positivement. Compte tenu de la littérature antérieure sur le VRC, ses réponses à l'entraînement et sa relation avec la performance, l'objectif de cette étude est de déterminer si le VRC matinal d'un joueur de hockey sur glace est une indication de l'efficacité d'un entraînement pré-compétition pour induire un effet PAPE positif. Un objectif secondaire de l'étude est d'explorer les différences entre les sexes dans les réponses à l'entraînement pré-compétition, ainsi que dans la relation entre le VRC et le PAPE.

Les participants ont été invités à effectuer un test de performance, sur la glace, au début de l'entraînement et le jour suivant, 4 à 6 heures après la séance d'entraînement à la résistance. Les participants ont été classés en deux groupes (élevé, faible) en fonction de leur score de VRC avant la séance d'entraînement. Une analyse ANOVA à deux facteurs a été réalisée pour déterminer les effets de la classification du VRC, du sexe et de l'interaction VRC-sexe sur les effets PAPE observés dans les différentes mesures de la performance. Les athlètes classés comme ayant un VRC faible ont connu une diminution significativement plus importante (p <

0,05) du temps de sprint moyen et une augmentation plus importante de la vitesse de sprint moyenne, mais aucune amélioration de la vitesse de sprint maximale n'a été observée. Les participantes féminines se sont améliorées ($p < 0,05$) plus que les participants masculins dans toutes les mesures de performance. Bien que la classification du VRC et le sexe aient eu des effets sur le PAPE, aucun effet d'interaction VRC-sexe n'a été observé.

Les résultats de l'étude peuvent être utiles aux entraîneurs de force et de conditionnement travaillant avec des joueurs de hockey sur glace. En surveillant le VRC d'un athlète le matin d'une compétition, un entraîneur peut être en mesure de déterminer objectivement comment l’athlète réagira à une séance d'entraînement pré-compétition et s'il est approprié d'en prescrire une. Ces informations peuvent éventuellement contribuer à mieux adapter et optimiser la préparation d'un athlète en vue d'une compétition.

Preface and Contribution of Authors

Maximilian Daigle was the primary author with roles in subject recruitment, data collection, analysis and interpretation, and thesis preparation.

Dr. Ross E Andersen, Professor, Department of Kinesiology and Physical Education, McGill University, the candidate`s supervisor, was actively involved with every step and decision made regarding the research study and the completion of this thesis.

Tricia Deguire assisted in participant recruitment and participant testing.

Chapter 1 – Introduction

1.1 Scope of the study

Sports science and the various fields of research examining potential ways to enhance athletic performance for ice hockey have grown over the last few years (Bizzini, 2022; Martini et al., 2022; Ronnestad et al., 2021). Formerly, professional ice hockey teams in the National Hockey League (NHL) engaged strength and conditioning coaches to oversee their player's physical development. Currently, many teams have hired sports performance experts, nutritionists, and sports psychologists, in addition to strength and conditioning coaches. Professional players are expected to report to their pre-season camps in peak physical condition. This is very different from the era when players reported to their team camps to get "in shape". Professional hockey has developed into a year-long profession, as athletes must spend their nine-to-twelve-week off-season period preparing themselves by undergoing rigorous resistance training and on-ice practices. The summer days of "drinking beer, swimming, and fishing" are over (Roberts, 2014).

NHL teams and their respective sports performance staff want to be sure their athletes are superbly conditioned, therefore, these performance coaches have improved their fitness testing protocols. For example, before being drafted by an NHL team, many draft-eligible players participate in the NHL combine tests, which include measurements of body composition, grip strength, lower body power (ex. vertical jump), and anaerobic power (ex. Wingate test) to name a few (Wood, 2008). All testing conducted at the NHL combine is taken into consideration when drafting young players.

Sports scientists are using testing and measurements to determine an athlete's physical abilities, in addition to monitoring players during a season to manage their stress and workloads to enhance recovery and on-ice performance (Buchheit et al., 2013). Assessing an athlete's heart-rate variability (HRV) has become increasingly popular in the field of sports performance as a means of monitoring a player's recovery status and optimizing their performance. Prior research has demonstrated that, in elite female soccer players, HRV is an indicator of their level of competition anxiety (Ayuso-Moreno et al., 2020). Moreover, there is a significant relationship between HRV and performance success in professional mixed martial arts athletes (Coyne et al., 2021). By using devices that measure HRV, such as the Omegawave device used in the research by Coyne and colleagues, sports scientists are better able to individualize an athlete's pre-competition preparation, which may help optimize game-day performance.

A specific aspect of sports preparation still under debate is the effectiveness of pre-competition training and the concept of post-activation performance enhancement (PAPE). PAPE is defined as an improvement in muscular performance following a conditioning activity, such as a barbell back squat (Lagrange et al., 2020). For example, an ice hockey player could perform a relatively high-intensity weight training session in the morning of an evening game as a means of potentiating or acutely improving their on-ice performance. However, research has shown both positive and negative effects on exercise performance (Scott et al., 2018; Till & Cooke, 2009), therefore questioning the effectiveness of PAPE. One potential reason for the equivocal results might be the complex factors involved with the effectiveness of PAPE, such as the athlete's muscle fiber type (Sweeney et al., 1993), the intensity of the pre-event exercise (McBride et al., 2005; Sotiropoulos et al., 2010), and the duration of recovery periods (Wilson et al., 2013). Although studies have reported equivocal findings, many studies share the same conclusion that there are no optimal conditions or protocols for inducing PAPE and that the effects are highly dependent on the individual athlete (Kobal et al., 2019; Sale, 2002). For example, one study examined the effects of maximal isometric squats on change of direction speed in elite rugby players and concluded that the squats did not improve performance; however, the researchers noted that there were some individual responders (Marshall et al., 2019). The ability to objectively determine whether an individual athlete is a responder or non-responder is, not currently being examined. This limits the strength coach's ability to know whether a pre-competition protocol is appropriate for an individual athlete, thus running the risk of potentially negatively impacting their athlete's performance.

1.2 Rationale

HRV has gained interest in the field of sports science as a tool to monitor training status measured both at rest (Plews et al., 2013; Stanley et al., 2013) and following exercise (Buchheit et al., 2010; Buchheit et al., 2008; Buchheit et al., 2013; Buchheit et al., 2012). HRV is a simple, low-cost, physiological marker that is being used in many sport science settings. Trainers and coaches are using this measure to assess athlete readiness and potentially overtraining status (Jack et al., 2019; Kraaijenhof, 2016). Some studies examining the relationship between performance and HRV have demonstrated that lower HRV is correlated with increased performance (Coyne et al., 2021; Morgan et al., 2007; Peterson, 2018). Concerning sex differences in HRV, females tend to have a higher HRV measurement than men (Koenig & Thayer, 2016; Ryan et al., 1994; Voss et al., 2015).

With the growth in research on the topic of HRV and sports performance, there is also an increased interest in the monitoring and management of HRV within the athlete setting. (Buchheit et al., 2010; Buchheit et al., 2008; Buchheit et al., 2013; Buchheit et al., 2012; Stanley et al., 2013). Several companies have introduced technologies that individual athletes can use to track their daily HRV (ex. Whoop Band and the Oura Ring). The current literature on HRV in sports performance has primarily emphasized the use of HRV in managing training loads (Kiviniemi et al., 2007; Sibony et al., 1995; Vesterinen et al., 2016), observing adaptations to training programs (Gratze et al., 2005; Iellamo et al., 2002; Pichot et al., 2000), and predicting performance (Morgan et al., 2007; Papacosta et al., 2016; Peterson, 2018). There is currently no research that has examined the relationship between an athlete's acute HRV measurement and their response to a pre-competition exercise training session.

Professional sports organizations are hiring sports scientists to maximize the potential of their athletes and gain an advantage over their opponents. One way to maximize athletic potential is to individualize the athlete's training and preparation leading up to competition. For example, with ice hockey players, it was seen that pre-competition training can improve on-ice performance 4 to 6 hours later through the effects of PAPE (Lagrange et al., 2020). Although there is evidence of performance improvements because of PAPE, there are still many questions regarding the effectiveness of PAPE. Previous literature on PAPE has examined physical variables, such as exercise intensity (McBride et al., 2005; Seitz & Haff, 2016; Wilson et al., 2013) and rest intervals (do Carmo et al., 2021; Seitz et al., 2015). The consensus regarding PAPE is that the effects on athletic performance are highly dependent on the individual and there is no single optimal protocol (Batista et al., 2011; McCann & Flanagan, 2010; Sale, 2002). This uncertainty of PAPE's effectiveness may leave sports coaches hesitant to utilize pre-competition training for their athletes, and there currently is no means to objectively measure how an athlete will respond or to predict who will respond.

With regards to ice hockey performance, there is little research examining the effects of PAPE on on-ice performance (Lagrange et al., 2020), and currently, no research exploring the relationship between HRV and PAPE effectiveness, in male or female athletes.

1.3 Purpose

The purpose of this study was to determine if an elite ice hockey player's morning HRV is predictive of how they will respond to a training session the morning of a game. We aimed to understand how an athlete's HRV score predicts the effectiveness of PAPE training, as well as explore whether there are sex differences in the relationship between HRV and pre-competition training. By understanding the relationship between HRV and the effect of PAPE training on ice hockey performance, a strength and conditioning coach may better tailor specific pre-game protocols for individual players to optimize their performance.

1.4 Hypothesis

Primary Aim: Examine the relationship between an athlete's HRV score and the effectiveness of a PAPE training for increasing on-ice performance in male and female collegiate varsity players.

Primary Measure: RMSSD (time domain metric of HRV).

HRV has been shown to predict athletic performance and training status (Peterson, 2018), and prior research has demonstrated that a greater vagal tone or a greater RMSSD value is linked to decreased performance (Coyne et al., 2020; Peterson, 2018). However, exercise training does decrease HRV by increasing sympathetic activity (Kingsley & Figueroa, 2016; Lewis & Short, 2010); therefore, it was hypothesized that athletes with greater HRV scores in the morning would experience improved performance after undergoing a pre-competition training.

Secondary Aim: Determine if sex differences exist and play a significant role in the relationship between HRV and PAPE effectiveness in improving performance.

Secondary Measure: Sex differences in the relationship between HRV and PAPE.

It has been reported that females tend to have higher HRV measures than their male counterparts. (Koenig & Thayer, 2016; Ryan et al., 1994; Voss et al., 2015), In addition, individuals with a higher HRV are less likely to perform optimally (Morgan et al., 2007; Peterson, 2018), there is greater vagal withdrawal, or decrease in HRV, when the training load is greater (Machado-Vidotti et al., 2014; Marasingha-Arachchige et al., 2022; Secher, 1985), and males, on average, have greater absolute strength than females (Bartolomei et al., 2021). With these factors to consider, it was hypothesized that male athletes would utilize a larger training load, induce greater sympathetic activation, and therefore, benefit more from the pre-competition training compared to their female counterparts.

Pilot Measures: We recognized that a lack of statistical power may limit the accuracy of between-sex analyses. However, little work on female ice hockey players has been done in the past (Chiarlitti et al., 2021). Thus, we planned to perform exploratory analyses to see whether a between-sex interaction existed among athlete readiness and performance variables in male and female varsity hockey players.

1.5 Delimitations

The following delimitations were identified for this study:

1) Participants were student-athletes at McGill University.
2) Participants were players from the 2023-2024 season.
3) Participants were aged between 18 and 25 years old.

4) Participants did not have any current or previous injuries that restricted their participation in the study (ex. musculoskeletal injury, concussion, etc.).

1.6 Limitations

The following limitations were identified:

1) It has been suggested that orthostatic HRV measures (performed during the transition from the supine to the standing position) are better suited for the measurement of team sport athletes (Rave & Fortrat, 2016). However, this suggestion is not consistent with the Omegawave instructions for measuring (Oy., 2020).
2) The study measured HRV the morning of performance testing, as well as right before testing. The literature on HRV recommends more frequent measurements (ex. weekly) to obtain reliable and valid scores to detect training adaptations (Plews et al., 2014). This study's purpose was to examine acute HRV and performance, not adaptations from training; therefore, acute measurements were appropriate.
3) To get an accurate HRV measure, it is recommended to avoid heavy physical activity and eat food 4 to 10 hours before testing (Hepburn et al., 2005; Sookan & McKune, 2012). However, hockey players practice almost every day and eat during the day of competition, thus, excluding this recommendation would make the procedure more representative of a hockey player's in-season experience.

1.7 Strengths

Both male and female athletes were represented in the study, which enabled the results to provide information on a larger scale. Also, the procedure was designed to mimic the conditions an ice hockey player would experience during a season. This increased the practicality of the results, as a strength and conditioning coach may utilize this technique with their athletes.

Chapter 2 – Literature Review

The world of professional sports is growing, as well as the stress an athlete experiences to compete at their best on every occasion. For example, the average salary of a National Hockey League (NHL) player has grown to where the average salary of a player in the NHL during the 2022-2023 season is greater than what the league's best player, Wayne Gretzky, was earning in 1990 (*1990-1992 Top 25 Salaries*; "What is the Average NHL Salary?," 2022). With the increased pressure to perform at their peak capacity during competition, athletes and coaches are striving to find new techniques to optimize their performance. One such way is through the monitoring of fatigue and recovery using HRV monitors (Pichot et al., 2002; Plews et al., 2013). Another recently explored tool is the use of pre-competition training (Lagrange et al., 2020). However, pre-competition training's application is not yet fully understood, making sports performance coaches somewhat hesitant to adopt it. Within this section will be a review of the literature on the topics of PAPE, HRV, HRV's relationship to sports performance, and the Omegawave Device, a non-invasive tool for monitoring athlete physiological readiness.

2.1 Post-Activation Performance Enhancement

Athletes utilize many different forms of preparation to ensure they are at their peak capacity for competition, including strength training, flexibility training, and mental performance preparation. Another common technique for enhancing performance is the undergoing of resistance training prior to competition to benefit from the effect of PAPE. PAPE is a physiological phenomenon that describes the increase in voluntary muscular performance following a conditioning activity (CA) (Blazevich & Babault, 2019; Prieske et al., 2020). For example, an athlete may perform a set of 5 repetitions of barbell back squats and experience an improvement in lower body power shown by an increase in countermovement jump (CMJ) height. Originally, the term used for PAPE was PAP, post-activation potentiation, however, there is a significant distinction between the two concepts. PAPE and PAP both represent an increase in muscular performance following a voluntary contraction, but PAP is verified through the use of electrical stimulation of the muscle, whereas PAPE is typically measured through voluntary performance such as jump height and sprint speed (Blazevich & Babault, 2019). It is important to note this difference, as it has been shown that the presence of PAP is not indicative of the presence of PAPE (Gossen & Sale, 2000).

Several mechanisms have been proposed for the increases in voluntary performance following a CA. One of the mechanisms proposed is the phosphorylation of the myosin regulatory light chain (MRLC) (Blazevich & Babault, 2019; Hodgson et al., 2005; Tillin & Bishop, 2009). When calcium is released from the sarcoplasmic reticulum during a muscle contraction, the phosphorylation of MRLC is activated by the enzyme myosin light chain kinase (MLCK). PAP occurs because MLCK brings the myosin head closer to its actin-binding site, making the likelihood of cross-bridge formation greater and increasing contractile force production. Although the phosphorylation of MRLC is involved with PAP, it is unlikely to be responsible for PAPE because of the difference in timing between the phosphorylation reaction and the occurrence of PAPE (Blazevich & Babault, 2019). Blazevich and Babault speculate that, since the phosphorylation occurs very rapidly, the increase in performance should be immediate, which is not what is observed in the literature. The removal of the phosphate from the MRLC also occurs soon after phosphorylation, therefore, considering that the effects of PAPE take minutes to become apparent and last for several minutes (Blazevich & Babault, 2019; Trimble & Harp, 1998), it is unlikely that phosphorylation of MRLC is a contributing mechanism of PAPE.

A previous muscle contraction has been shown to raise the excitability of the alpha-motoneurons, which results in an increased contribution of Type 2 fast-twitch muscle fibers to subsequent muscle contractions (Golas et al., 2016). This increase in fast-twitch muscle fiber involvement can explain the improvement in explosive performance and may demonstrate that improved motoneuron excitability is a contributing factor to PAPE. Hirst et al (Hirst et al., 1981) found that larger excitatory post-synaptic potentials (EPSP) from stimulation of motoneurons increase the likelihood of initiating an action potential on the motor endplate and contracting the muscle fiber. In addition to enhanced motoneuron excitability, there is an increased neurotransmitter release and improved efficiency of neurotransmitter signaling (Tillin & Bishop, 2009). These improvements are primarily found in larger motoneurons (those associated with fast-twitch skeletal muscle fibers), which corroborates previous research showing that there is increased fast-twitch fiber contribution in following contractions (Golas et al., 2016; Luscher et al., 1983). Finally, the H-wave amplitude, a function of the number and size of recruited motor units (Hugon, 1973), is elevated 5-13 minutes following a maximal voluntary contraction (MVC). The potentiation observed is an indication of increased motoneuron excitability, neurotransmitter release, and assumption that the larger motor units would be preferentially recruited after a conditioning activity (Hodgson et al., 2005), resulting in the enhancement of muscular performance.

Other mechanisms that have been shown to be involved with the induction of PAPE are an increase in muscle temperature and an increased level of arousal (Blazevich & Babault, 2019; Schmidt et al., 2009). An increase in muscle temperature is associated with an increase in rate of force development (RFD) and muscle shortening velocity as a result of an increased rate of cross-bridge cycling from the temperature-sensitive enzyme, myosin ATPase (Stein et al., 1982).

Finally, it was demonstrated that increased arousal levels were associated with increased force output (Schmidt et al., 2009), most likely due to an alteration in the neurochemical balance of the brain involving neurotransmitters such as norepinephrine (Berridge et al., 2012; Cairns & Borrani, 2015).

The concept of PAPE has been studied in the field of sports performance, primarily examining its efficacy in improving athletic performance and attempting to establish optimal standards for eliciting a benefit (Kilduff et al., 2011; Lagrange et al., 2020). A study looking at the effects of contrast training, or the execution of an explosive movement following a movement with a heavier load, as a conditioning activity on ice-hockey performance found that the protocol improved the athlete's sport-specific performance (Lagrange et al., 2020). The athletes underwent the vertical CMJ test, a broad jump test, and an on-ice repeated sprint ability test. The experimental group performed the contrast training protocol 6 hours prior to the physical testing. There was no significant change in jumping abilities 6 hours post-training, however, the experimental group experienced a significant improvement ($p < 0.05$) in total sprint time (-5.5%), mean sprint speed (+5.9%), and in the first sprint speed (+7.4%), while the control group did not show improvements in any of these measures. These conclusions demonstrated that performing a PAPE protocol before competition may improve the athlete's ability to perform in their respective sport and possibly provide them with an advantage over their opponents. Other studies also demonstrated similar benefits of performing resistance training before competition (Bompa & Buzzichelli, 2015; Kilduff et al., 2011). For example, a study found an increase in power output during the CMJ test in a group of international sprint swimmers (Kilduff et al., 2011). This demonstrated the acute benefits of resistance training on performance because there is a significant correlation between the CMJ test results and sprint speed (Meylan & Malatesta, 2009; Wisloff et al., 2004), as well as in change of direction ability (Meylan & Malatesta, 2009). The equivocal results seen across the studies by Lagrange et al (Lagrange et al., 2020) and Kilduff et al (Kilduff et al., 2011) regarding CMJ performance may be partially explained by the different recovery periods between the stimulus and measurement, as the former study performed the PAPE protocol 6 hours before testing, whereas the latter study measured CMJ within minutes after the conditioning activity. Aside from the differences in methods and time intervals, the conclusions of these studies suggest that by harnessing the effects of PAPE by including a CA before a sporting event requiring explosiveness and speed, an athlete can enhance their physical capabilities.

Although there is substantial evidence of the presence of a PAPE effect following a conditioning activity, there is also research demonstrating either no effect or a negative effect of undergoing a conditioning activity on performance (Chiu et al., 2003; Hanson et al., 2007; Marshall et al., 2019; Till & Cooke, 2009). Marshall et al (Marshall et al., 2019) examined the effect of performing a maximal isometric squat on an athlete's ability to perform the pro-agility test. By having the athletes perform 3 sets of a 3-second maximal isometric squat and a 2-minute recovery period between sets, they showed that the conditioning activity did not have an enhancing effect on an athlete's performance. However, it is possible that the conditioning activity stimulus was not large enough to elicit a potentiating effect, therefore, explaining the lack of effect observed. Another study demonstrated a negative effect on jumping performance, evidenced by a decrease in jumping ability (Chiu et al., 2003), however, the decrease was only found in recreationally trained participants. The explosively trained athletes experienced increased performance after the conditioning activity.

The conflicting evidence regarding the efficacy of exercise on PAPE may be attributed to a variety of factors contributing to whether an athlete experiences the effects of PAPE, as it has been stated that there is a lack of optimal standards for the pre-performance exercise (Kobal et al., 2019; Sale, 2002). These factors include the proportion of slow to fast-twitch muscle fibers an athlete possesses, the athlete's strength level, the exercise intensity (percentage of a 1-repetition maximum (1RM)), and the rest interval between the CA and performance assessments.

PAPE has been shown to be more effective in athletes with a greater proportion of fast-twitch muscle fibers because these fibers undergo a greater magnitude of phosphorylation (Hodgson et al., 2005; Moore & Stull, 1984; Sweeney et al., 1993). The reason for this is that Type 2 muscle fibers are more sensitive to increases in calcium and have greater MLCK activity (Moore & Stull, 1984), resulting in higher levels of MRLC phosphorylation. Although myosin phosphorylation is suspected to not play a significant role in PAPE (Blazevich & Babault, 2019), the importance of muscle fiber contribution to PAPE effectiveness is related to the influence an athlete's strength level has on achieving maximal PAPE benefits. Muscle fiber dominance is correlated with an athlete's strength level, with stronger athletes typically having a greater proportion of fast twitch fibers (Aagaard & Andersen, 1998; Maughan et al., 1983; Thorstensson et al., 1976). The finding that stronger individuals experience greater effects from PAPE (Kilduff et al., 2007; Seitz et al., 2015; Wilson et al., 2013) suggests that the muscle fiber composition may influence the conditioning activity's ability to improve performance.

Regarding the association between relative strength and effectiveness of pre-performance test exercise, Seitz and Haff (Seitz et al., 2015) specify that athletes with the ability to squat greater than 1.75 times their body weight on the Barbell Back Squat show greater improvements in performance. Even though stronger athletes show a greater PAPE effect, this does not mean that weaker individuals will not demonstrate improved athletic capabilities following resistance training. A recent study showed that weaker athletes responded more favorably to exercise in the intensity range of 60% to 70% of their 1RM, whereas stronger individuals responded better to a higher-intensity stimulus (greater than 90% 1RM) (Golas et al., 2017), which could be related to training status or the stronger athletes' ability to tolerate heavier loads and greater stimuli. Although there is evidence that training background is a contributing factor to the effectiveness of resistance training on eliciting a PAPE effect, Batista et al (Batista et al., 2011) found otherwise. PAPE effects were compared between three groups of individuals with very different strength training experience (bodybuilding, track and field, and physically active). What was concluded from the research was that there was no significant effect of training background on the effects of PAPE (Batista et al., 2011). The conflicting findings of this study may be explained by the PAPE protocol selected for the study. Participants performed either 1 or 3 sets of 5-second maximal isometric contraction on the 45-degree leg press machine with 3 minutes of recovery between sets. The stimulus may not have been strong enough to elicit a potentiation effect and is not as well transferable to more complex motor tasks (Wilson & Murphy, 1996) like a maximal CMJ. In addition, an isometric contraction would not stimulate as many muscle fibers as a full-range, isotonic contraction.

One important factor of PAPE that is well understood is the notion that PAPE relies on the delicate balance between potentiation and fatigue (Tillin & Bishop, 2009). Fatigue dissipates at a faster rate than potentiation (Scott et al., 2018), however, if a voluntary contraction is performed without adequate recovery, or before fatigue has decreased to a level at which potentiation is greater than fatigue, performance will be negatively impacted. This was demonstrated in the amplitude of the H-reflex, in which it was found to be depressed for 10 to 60 seconds following the CA (Gullich & Schmidtbleicher, 1996; Trimble & Harp, 1998). Although potentiation was negatively impacted during the initial stage of recovery, it was significantly enhanced afterward (Gullich & Schmidtbleicher, 1996). In a meta-analysis conducted by Wilson et al (Wilson et al., 2013), it was found that the optimal recovery interval to elicit a performance improvement was 7 to 10 minutes after the activity. Research, however, has failed to provide a consensus regarding the "perfect" interval, as other studies show as low as 5 minutes (Seitz et al., 2015) and as high as 12 minutes (Gahreman et al., 2020) following the cessation of exercise. The benefits of exercise training on improving performance have even been shown to be retained for hours after the CA (Bompa & Buzzichelli, 2015; Chiu et al., 2004; Lagrange et al., 2020). Due to diversity in the prescription of rest intervals, do Carmo et al (do Carmo et al., 2021) studied how allowing an athlete to self-select their rest interval compared to using a pre-determined 4-minute rest interval. Within the subject group that experienced enhanced performance, there was a large variation in their individually selected rest times (Table 1), with the lengths averaging 5:57 +/- 2:44. This demonstrates that the rate at which an athlete recovers from the conditioning activity and experiences the beneficial effects of PAPE is highly individualized.

Table 1.

Percent changes in countermovement jump performance following either a fixed or self-selected rest interval. (do Carmo et al., 2021)

Participant	Fixed Rest Interval Group	Self-Selected Rest Interval Group	Self-Selected Rest Interval Duration
4	1.3	6.7	8:00
7	1.7	13.6	6:13
8	-2.0	16.2	9:20
11	-1.4	18.2	8:22
12	0.1	12.0	3:19

When designing a training protocol to potentiate an athlete without accumulating too much fatigue, the intensity (percentage of an athlete's 1RM) of the exercise is another important factor to consider. A meta-analysis concluded that a load of 60% to 85% of a 1RM is superior to other intensities (Wilson et al., 2013), the research regarding the optimal intensity remains inconclusive. There is some evidence demonstrating that high intensity (greater than 85% 1RM) is superior (McBride et al., 2005; Seitz et al., 2015) to medium (60% to 84%) and low intensities (less than 60%). McBride et al (McBride et al., 2005) examined the difference between a heavily loaded squat (1 set of 3 repetitions at 90% 1RM), a loaded CMJ (1 set of 3 repetitions at 30% 1RM), and a control group (4-minute walk). Following a 4-minute recovery after the CA, the participants completed a timed 40m maximal sprint, with their times measured at 10m, 30m, and 40m. What the researchers found was that the high-intensity protocol (heavily loaded squat) resulted in 0.87% ($p = 0.018$) faster 40m sprint time. In contrast, there is also evidence contradicting the findings of McBride et al, as it was seen that a 3RM back squat failed to improve CMJ performance (Mola et al., 2014). The main finding of this investigation was that high-intensity squats were ineffective at improving CMJ height, but there were PAPE responders among the group of participants. The participants of the study (Mola et al., 2014) were inexperienced in terms of strength training (1 year of experience with resistance training) and possibly did not have the required level of strength and skill for the CA to be effective, as suggested by Seitz and Haff (Seitz et al., 2015), which could explain the lack of improvement in CMJ height following a high-intensity CA.

High-intensity exercise is not the only form of exercise shown to be beneficial. Numerous studies have shown that performing a CA with a moderate intensity load (60-84%) is optimal (Krzysztofik, Wilk, Filip, et al., 2020; Smilios et al., 2005; Sotiropoulos et al., 2010;

Wilson et al., 2013). Smilios et al (Smilios et al., 2005) examined the effects of performing a loaded half squat or a loaded jump squat with both 30% and 60% of the athlete's 1RM on improving CMJ performance. The results showed that a loaded half squat with 60% and a loaded jump squat with 30%, increased the athlete's subsequent CMJ height. This conclusion was confirmed by another study demonstrating that low to moderate loads of 25% to 60% improved muscle power (Sotiropoulos et al., 2010). When comparing the effectiveness of either high or moderate intensity, moderate intensity was superior. A meta-analysis examining the difference between ballistic-plyometric exercise, moderate loading (60-84%), and heavy loading (greater than 85%) on the bench press exercise concluded that moderate loading was the most effective intensity at inducing PAPE on subsequent explosive bench press lifts (Krzysztofik, Wilk, Stastny, & Golas, 2020).

Based on the prior research examining the different factors (rest, intensity, etc.) included in the programming of a PAPE protocol, it is evident that there is no clear consensus regarding what is optimal for each training variable (Sale, 2002). However, investigators agree that the effects of PAPE are highly dependent on the individual athlete (Batista et al., 2011; Golas et al., 2016; Kobal et al., 2019; Marshall et al., 2019; McCann & Flanagan, 2010; Till & Cooke, 2009). In a study comparing the effects of three different PAPE stimuli (deadlift, plyometric tuck jump exercise, and isometric MVC knee extension) on sprinting and jumping performance, no significant difference was found between stimuli (Till & Cooke, 2009). However, the conclusion from the data was that there was a large variation in individual responses between conditions (-7.1% to 8.2%), implying that individuals may respond differently based on the exercise selected. This supports the findings from a study by McCann and Flanagan (McCann & Flanagan, 2010) demonstrating that some individuals have greater PAPE responses by performing power exercises (ex. Olympic lifting), while others benefit more from strength exercises such as the barbell squat. Besides exercise selection, intensity and volume are also dependent on the individual and lack optimal standards. Kobal et al (Kobal et al., 2019) compared the use of different loads (1RM, 3RM, 5RM, and 60% of 1RM) on the barbell half-squat to determine which intensity was more effective at eliciting a PAPE effect. A main finding of the study was that individuals were responsive to at least one of the protocols, and thus, demonstrated a preference for a particular intensity range or load. Finally, in some studies demonstrating no benefit of performing a conditioning activity towards voluntary muscular performance, they found some individual responders among the group of participants (Batista et al., 2011; Marshall et al., 2019).

Currently, there is no consensus regarding optimal conditions for the multitude of factors influencing PAPE effectiveness, such as volume, intensity, and rest interval (Sale, 2002). However, one aspect of PAPE that has not been previously examined was the relationship between the balance of an athlete's autonomic nervous system (ANS) and the effects of PAPE. HRV is a tool to monitor the balance between the two autonomic branches (Malmo & Shagass, 1948). The balance, quantified by HRV, is heavily influenced by exercise and an athlete's training state (Borresen & Lambert, 2008; Kaikkonen et al., 2008; Mayo et al., 2016), while also having a significant effect on athletic performance (Coyne et al., 2021; Peterson, 2018). HRV monitoring has even been shown to be a predictor of performance and athlete readiness (Coyne et al., 2021; Peterson, 2018). Due to the relationship between HRV and sports performance, HRV measuring may potentially be a useful tool to predict whether individuals will be responders or non-responders.

2.2 Heart Rate Variability

The ANS is a critical part of the central nervous system (CNS). The ANS receives afferent input from the central nervous system (CNS) (Loewy, 1990) based on the stimuli presented to the body and relays the efferent information to the target organs throughout the body to elicit a response (Loewy, 1990). The ANS is divided into the sympathetic nervous system (SNS) and the parasympathetic nervous system (PNS), with both systems constantly working to maintain homeostasis in the body. Both subdivisions are composed of pre-ganglionic fibers and relay the signals to the post-ganglionic fibers, which act on target organs (Loewy, 1990). The parasympathetic pre-ganglionic neurons are involved with the control of vagal (parasympathetic) output and connect with the post-ganglionic neurons of the heart, respiratory tract, and other tissues to modulate parasympathetic control of the organs (Huang et al., 1993).

Concerning exercise science, the ANS is heavily involved with the control of blood pressure. The ANS sends afferent signals through the pre-ganglionic parasympathetic and sympathetic neurons to modulate cardiac output and vascular resistance in an attempt to regulate changes in blood pressure (Benarroch, 2008; Smit et al., 1999). The sympathetic modulation acts as a vasoconstrictor to the vessels, whereas the parasympathetic input has a vasodilatory effect (Gibbons, 2019). Along with control over vascular resistance, the ANS influences heart rate. Decreased vagal tone (PNS activity) to the heart increases heart rate, while the opposite holds when there is an increase in parasympathetic modulation (Gibbons, 2019).

A common method of measuring ANS activity, or more so the balance between the SNS and PNS, is the measurement of an individual’s heart rate variability (HRV) (Malmo & Shagass, 1948). HRV is the variability in cardiac cycles or R-R intervals. Not only is HRV used in a clinical setting, it has also made its way into the realm of sports science because it is one of the most popular tools for objectively monitoring athlete's recovery and performance (Buchheit, 2014). The use of a short (1-5 minute) HRV assessment has been shown to be an effective method of measuring HRV (Dobbs et al., 2019; Esco & Flatt, 2014). A reason why HRV has been demonstrated to be a tool for measuring the status of the ANS is that the ANS directly influences the changes in inter-beat intervals through sympathetic and parasympathetic modulation (Aubert et al., 2003). The degree of variance between cardiac cycles indicates the balance between the two subdivisions of the ANS.

There are many methods of quantifying HRV. Measurement of HRV can be divided into two categories: Frequency (spectral) domain and Time domain. The key methods of the Frequency domain are the High Frequency (HF), the Low Frequency (LF), and the LF/HF ratio. HF reflects the level of parasympathetic activity (Pagani et al., 1986; Vitale et al., 2019), as it is modulated by the PNS branch (Berntson et al., 1993), and is found in the activity range of 0.15 to 0.40 Hz. The LF is proposed to be mediated by both sympathetic and parasympathetic activity (Morgan et al., 2007) and is represented by activity in the 0.04 to 0.15 Hz range. Although the spectral components are measured separately, it has been suggested that it is more appropriate to consider the LF/HF ratio, as it represents the balance between the two systems (Bilchick & Berger, 2006; Pagani et al., 1986). An increase in the ratio, resulting from an increase in physical or psychological stress, is an indication of a shift in the balance as there is an increased contribution of the SNS (Claiborne et al., 2021; Pagani et al., 1986).

The primary time-domain methods of quantifying HRV are the Standard Deviations of NN Intervals (SDNN) index and the root mean square of successive RR interval differences (RMSSD). The SDNN index is considered the "gold standard" for quantifying the potential for cardiovascular risks ("Heart rate variability. Standards of measurement, physiological interpretation, and clinical use. Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology," 1996) and primarily reflects the overall function of the ANS (Li et al., 2022). The SDNN is computed from 24-hour recordings, which makes this measurement impractical in the context of athletic performance. RMSSD, or the natural logarithm of RMSSD (lnRMSSD), is associated with PNS activity (Li et al., 2022) and is more commonly used in sports science (Buchheit, 2014) as it is considered the most useful metric to quantity HRV based on a short 5-minute recording (Buchheit, 2014). Not only is using the RMSSD value more practical, but lnRMSSD has also been shown to be related to changes in performance (Da Silva et al., 2014) and can objectively detect states of fatigue (Mourot et al., 2004; Schmitt et al., 2013; Schmitt, Regnard, et al., 2015).

Based on an individual's recording and calculated HRV, the values provide insight into the balance between the PNS and SNS. In an individual with a higher HRV, the parasympathetic modulation is dominant (Algra et al., 1993). A lower HRV signifies that the individual is highly influenced by the sympathetic nervous system (Umetani et al., 1998). When examining the difference between males and females, females tend to display higher HF power in HRV measurements, indicating a greater parasympathetic tone (Koenig & Thayer, 2016; Ryan et al., 1994). For example, a study by Sookan and McKune (Sookan & McKune, 2012) demonstrated that males had 13% higher LF values and a 41% greater LF/HF ratio, while females had a 12% higher HF power. Age is another factor that influences an individual's HRV. In general, HRV decreases with an increase in age (Averyanova, 2023; Geovanini et al., 2020; Zulfiqar et al., 2010). There is a decrease in both sympathetic and parasympathetic activity, however, the decrease in HRV is primarily a result of the decreased vagal tone in older individuals (Averyanova, 2023; Zulfiqar et al., 2010). Finally, the literature does not suggest any specific foods that significantly affect HRV. However, sodium consumption does seem to influence HRV, as a low-sodium diet was seen to increase sympathetic activity while a high-sodium diet is associated with an increase in parasympathetic tone (Allen et al., 2014).

2.3 HRV and ANS Relation to Exercise and Sport

The interest in HRV and its relation to exercise and sports performance has grown substantially over the years. Research has examined the effect exercise has on HRV, the kinetics of HRV during the post-exercise recovery period, how HRV has been used as a means of managing training loads, and even HRV's ability to predict athletic performance. The basis of the research revolves around the relationship between the two ANS branches (SNS and PNS) and exercise. Changes in emotional states (ex. psychological arousal during exercise) are associated with changes in parasympathetic and sympathetic activity, which ultimately alters the LF/HF ratio (Virtanen et al., 2003). For example, the SNS is activated in anticipation of challenges as a means of preparing the different systems of the body to combat the challenges ahead (Freeman, 2006). One of these changes is an increase in heart rate and blood pressure, which results from the SNS-mediated release of epinephrine and norepinephrine (Selye, 1946, 1950). It was later suggested that the ANS plays a significant role in the response to training stressors (Hautala et al., 2009; Hautala et al., 2003, 2004) and that the ability of the ANS to respond to stressors, quantified by HRV measurements, may indicate the body's physiological ability to adapt to the training (Aubert et al., 2003).

Previous research has shown that exercise does have a significant effect on HRV. During exercise, there is a gradual decrease in HRV and parasympathetic tone, along with an increase in sympathetic drive (Borresen & Lambert, 2008; Casties et al., 2006; Goldberger et al., 2006; Kaikkonen et al., 2008). Change in the balance between the two systems is mediated primarily by the increased activity of the adrenergic neurotransmitters, epinephrine, and norepinephrine. These neurotransmitters bind to the post-ganglionic neurons associated with the heart and increase heart rate (Borresen & Lambert, 2008). The decrease in HRV is represented by an increase in the LF/HF ratio, which indicates an upregulation of SNS activity and downregulation of parasympathetic tone, and a decrease in RMSSD, an indicator of PNS activity (Becker et al., 2021). Although it is accepted that HRV decreases with exercise, changes in LF power are only associated with medium to high-intensity exercise and not with low-intensity exercise (Perini & Veicsteinas, 2003). It is suggested that this observation may be due to the relationship between HRV and the magnitude of perceived exertion and lactate levels in the blood (Kaikkonen et al., 2010). Low-intensity exercise may not increase lactate levels in the blood sufficiently to alter the activity of both the PNS and SNS.

HRV has been examined as a tool to manage an individual's training program and recovery, as changes in HRV following a single session of exercise are suggested to be an indication of the balance between exercise stress and recovery (Sibony et al., 1995). The cessation of an exercise session causes another change in HRV, primarily an increase in vagal activity and a decrease in sympathetic drive (Savin et al., 1982). This manifests itself in an increase in HRV, a decrease in blood pressure and heart rate, and a general feeling of relaxation (Selye, 1946, 1950). However, this increase in PNS control may take time, as it has been shown that parasympathetic activity and RMSSD can be reduced for up to 1 hour after an acute resistance training session (Heffernan et al., 2008; Lewis & Short, 2010; Rezk et al., 2006)**.** A primary factor contributing to the delayed recovery of parasympathetic tone is the intensity of exercise. High-intensity exercise can alter ANS activity for more than 24 hours (Al Haddad et al., 2009; Stanley et al., 2013), with some research even suggesting HRV reductions for as long as 72 hours before returning to normal (Imai et al., 1994; Seiler et al., 2007). The greater intensity training causes a shift in the autonomic balances to a sympathetically dominant state during exercise (Hynynen et al., 2006) and remains in this state during the early recovery phase (Chen et al., 2011). This is further demonstrated in a study by Marasingha-Arachchige and colleagues (Marasingha-Arachchige et al., 2022) in which they showed that there was a reduction in RMSSD and HF, both indications of PNS withdrawal (Ernst, 2017; "Heart rate variability. Standards of measurement, physiological interpretation, and clinical use. Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology," 1996; Shaffer & Ginsberg, 2017), and an increase in LF and the LF/HF ratio, suggesting a sympathetically dominated system (Ernst, 2017; "Heart rate variability. Standards of measurement, physiological interpretation, and clinical use. Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology," 1996). To summarize, following exercise, the nervous system remains in a sympathetically dominant state for up to 72 hours, after which there is an increase in vagal tone and a withdrawal of SNS activation.

An often-forgotten aspect of athletic performance is the cognitive ability of an athlete during competition. HRV has not only been examined in the context of physical exercise, but also concerning cognitive function. For example, a study examined the correlation between HRV and performance on tests of executive function and memory and found that individuals with higher baseline HRV scores performed better than those with low HRV (Hansen et al., 2003). Lower HRV was also found to be related to poor performance in global cognition (Kim et al., 2006; Mahinrad et al., 2016; Melis & van Boxtel, 2001), poor visuospatial performance (Frewen et al., 2013), poor overall cognitive performance and a greater decline in processing speed (Mahinrad et al., 2016). Although much of the research suggests a lower HRV is indicative of poor performance, there is evidence that increased sympathetic tone or decreased vagal control may increase attention (Porges et al., 1996) as it has been shown that greater SNS activity is associated with greater cognitive demands (Mukherjee et al., 2011). This relationship was evident in the research by Fuentes-Garcia and colleagues (Fuentes-Garcia et al., 2019), in which they examined the correlation between the difficulty of chess problems, performance on the problems, and the individual's HRV. What was concluded from the research was that as the difficulty of the task increased, HRV decreased in both high and low-performing groups. However, the between-group analysis showed that HRV was significantly higher in the high-performing group compared to the low-performing group. The higher HRV may be associated with a greater ability to control their focus and attention on the task at hand (Park et al., 2013). This demonstrated that there is an increase in sympathetic activity as cognitive demands are increased, but a greater HRV was associated with better cognitive performance.

An athlete's goal with training and practice is to improve their skill set and sporting abilities. For that to occur, the proper training loads and stressors must be applied for the athlete to properly adapt and develop. One physiological system that plays a crucial role in the adaptation response to training is the ANS (Hautala et al., 2003, 2004), which may be why HRV research on athletic performance improvements and load management has become popular. Evidence indicates that an increase in parasympathetic control reflects an increase in physiological fitness (Abad et al., 2014; Gratze et al., 2005; Iellamo et al., 2002; Pichot et al., 2000). This was shown in a study measuring the ANS balance of long-distance runners during a training intervention (Buchheit et al., 2010). Of all the participants in the study, only those who experienced a greater than 0.5% improvement in 10-kilometer running times showed progressively increased PNS activity during the training period (Buchheit et al., 2010). The relationship between increased PNS tone and improved cardiovascular fitness is an indication that HRV analysis may be a useful tool for tracking athletic development (Botek et al., 2014; Earnest et al., 2004; Oliveira et al., 2013).

Increased vagal control is linked to improved fitness levels; however, a reduction in HRV may be an indication of decreased athletic performance, poor adaptation to training, or accumulated fatigue (Pichot et al., 2002; Plews et al., 2013; Uusitalo et al., 1998). It is suggested that an athlete demonstrating an ANS with elevated sympathetic activity at rest may be in a state of decreased fitness or recovery level (Bosquet et al., 2008; De Meersman, 1993; Hynynen et al., 2006). The decrease in HRV observed in athletes is related to an increase in sympathetic activity and a withdrawal of vagal activity, most likely occurring because of an increase in training load or resistance (Kingsley & Figueroa, 2016). When comparing the HRV changes and autonomic balance following either lower-body or an upper body resistance training, there was a significant increase in sympathetic activity after the lower-body training (Machado-Vidotti et al., 2014). This is suggested to be caused by the fact that greater loads (resistance) were used for the lower body (Parallel Squat) than the upper body (Bench Press) exercise, thus recruiting more muscle units, placing more stress on the body, and activating the SNS to a greater extent (Mayo et al., 2016). Besides training load, training volume and training to muscular failure are both significant factors contributing to the magnitude of HRV changes. Training volume was shown to influence RMSSD, LF, and HF values in athletes (Marasingha-Arachchige et al., 2022). A higher training volume induced greater activation of the SNS and withdrawal of vagal activity, thus resulting in a greater decrease in HRV (Secher, 1985). More specifically, when 3 or more sets were performed for an exercise, the training had a significant effect on lowering parasympathetic levels (Figueiredo et al., 2015). Not only did the number of sets performed contribute to changes in ANS balance, but also the proximity to failure reached during the sets. Gonzalez-Badillo and colleagues (Gonzalez-Badillo et al., 2016) examined the difference between performing sets to failure (3 sets x 8 repetitions) and performing half the number of repetitions (3 sets x 4 repetitions) with the same load on HRV and neuromuscular fatigue. What they found was that the 3 x 8 protocol resulted in much greater neuromuscular fatigue, indicated by a larger decrease in CMJ performance, and a greater decrease in HRV 6 hours post-exercise. The finding that training to failure results in greater decreases in HRV was further supported in a study by Mayo and colleagues (Mayo et al., 2016).

When an athlete has a lower HRV score at rest, it is a sign that their ANS is in a predominantly sympathetic state. This disruption in ANS balance may result in the athlete having a decreased ability to react to further stressors such as exercise (Forte et al., 2019; Shaffer et al., 2014). This suggests that the athlete would not be able to adapt to their training to improve and may potentially have further negative consequences on the recovery of their ANS. The concept of HRV-guided was introduced to manage an athlete's training loads as a means of preventing the athlete from entering a state of overtraining. Basing training and load prescriptions according to HRV scores has been shown to be effective (Kiviniemi et al., 2007; Vesterinen et al., 2016). One study compared the performance improvements between HRV-guided trainees and a standard training group (Kiviniemi et al., 2007). The HRV-guided group's training was based on the difference between their PNS activity from the day prior. If parasympathetic indices were similar or higher than the previous day, the athlete completed a high-intensity training session. If parasympathetic activity was lower, a rest day or low-intensity session was prescribed. At the end of the study, the HRV-guided trainees had 2 times greater maximal running velocity than the standard training group, even if the standard group had a slightly higher overall weekly training load. This study provides evidence that HRV parameters can be used to monitor recovery and provide appropriate training loads (Dong, 2016; Ferreira et al., 2015; Plews et al., 2013).

Besides being used as a monitor of training load and progress, HRV can be utilized in the management of players immediately prior to competition. The Yerkes and Dodson theory (Yerkes, 1908) refers to the relationship between performance and arousal. According to the theory, an individual has an optimal range of arousal level at which performance is maximized, and a hypo- (below) or hyper-aroused (above) state will result in a decrease in performance. In relation to athletic competitions, athletes typically experience feelings of nervousness or anxiety before critical performances, such as a final or playoff match, which manifests itself in a lower HRV (D'Ascenzi et al., 2014). Higher stress levels may affect the ratio between the two autonomic systems, with a predominance of sympathetic tone, as seen in the change in the LF/HF ratio (Souza et al., 2019). The level of anxiety and arousal is dependent on the level of the athlete, with higher-level athletes showing less pre-competitive anxiety, as demonstrated in the comparison between international and national level judo athletes (Morales et al., 2013). Another study by Ayuso-Moreno and colleagues (Ayuso-Moreno et al., 2020) examined the relationship between pre-competitive anxiety and HRV. What was found was that, prior to lower demanding matches, HRV remained unchanged compared to baseline; however, HRV was reduced before an important competition. The HRV metrics determined to be markers of pre-competitive anxiety were SD1 and RMSSD scores (Ayuso-Moreno et al., 2020). Although the Yerkes and Dodson theory infers that a hyper-aroused state has a negative effect on performance, the relationship between HRV, anxiety, and performance is inconclusive. Athletes with higher levels of anxiety in a competitive situation have been shown to experience decreases in performance (Scanlan T, 1979; Sonstroem, 1984). On the other hand, studies have found that higher arousal and sympathetic activation can increase performance through improved psychological preparedness and attention (Morgan et al., 2007; Papacosta et al., 2016). Morgan and colleagues performed a series of studies on students from the US Navy SERE school (Morgan et al., 2007). The first study hoped to see the correlation between HF power and student performance during a captivity interview test. What was concluded was that a decreased vagal tone (lower HF power) predicted superior performance during the test. The second study then examined the HF metric's ability to predict performance during an underwater navigation exam. Once again, decreased parasympathetic activity predicted better performance during the stressful test. In summary, the study concluded that a reduction in baseline parasympathetic tone appeared to be related to greater performances on complex tasks.

An individual's lower HRV may be predictive of a better performance in fields other than athletics; however, similar findings were seen in studies with high-level athletes (Coyne et al., 2021; Peterson, 2018). In a study looking at the HVR of mixed martial arts athletes, a lower HRV was significantly correlated ($r = 0.55$; $p < 0.01$) with performance (Coyne et al., 2020). It was hypothesized that there is an increased requirement of sympathetic activity necessary to optimize performance. This may be a result of the relationship between increased neurotransmitter release (norepinephrine, epinephrine) and improved muscular performance (Cairns & Borrani, 2015; Williams & Barnes, 1989). Another study looked at the potential predictive ability of an NCAA Division 1 track and field athlete's RMSSD score and their sprint performance (Peterson, 2018). Similar to the study by Coyne et al (Coyne et al., 2020), a higher lnRMSSD and increased parasympathetic tone were associated with increased race times. What was concluded was that an athlete experienced poor performance when their nervous system was in a predominantly parasympathetic state. The researchers stated that the most desirable lnRMSSD range for an athlete to maximize performance was between 4.0 and 4.2ms. What these studies by Peterson and Coyne et al indicate is the potential utility of HRV testing as a means of measuring an athlete's autonomic state before competition and using exercise to get them into that optimal range proposed by Yerkes and Dodson (Yerkes, 1908).

2.4 Omegawave Technology

There are many HRV monitoring devices on the market, one of them being the Omegawave (Omegawave, Espoo, Finland), which has been used in previous sports performance research (Coyne et al., 2020; Heishman et al., 2018). The Omegawave device includes an electrocardiogram (ECG) chest strap, two electrodes (one placed on the forehead, the other on the base of the right-hand thumb), and a sensor. The device measures HRV and Direct Current (DC) potential (Berkoff et al., 2007; Peterson, 2018). DC potential is suggested to be an indicator of the state of the nervous system and is correlated with electroencephalography (EEG) measures (Coyne et al., 2020; Valenzuela et al., 2020). The technology then combines the two measurements and provides an "overall readiness score" (0-7) to quantify the athlete's physiological readiness to perform (Morris, 2015). The Omegawave has been shown to be correlated to previously existing HRV monitoring methods and has been presented as a reliable HRV measuring tool (Naranjo-Orellana et al., 2021). This technology is utilized by some of the most renowned European soccer clubs, including AC Milan (Italy), Bayern Munich (Germany), FC Barcelona (Spain), and Manchester United (England) (Csapo R).

Previous research that utilized the Omegawave device as a measure of athlete readiness has shown that it can be a valuable tool for an athletic performance coach. Peterson (Peterson,

2018) found that the RMSSD and DC potential measured on NCAA Division 1 Sprinters predicted how well they would perform in competition. More specifically, the higher an athlete's vagal tone and greater parasympathetic dominance, seen by a greater lnRMSSD value, the slower their sprint times were. However, sprint times were only significantly affected when the lnRMSSD value was above 4.4ms. The consensus from the results was that optimal performance was achieved in the 4.0 to 4.2ms range.

Another study examining the relationship between Omegawave results and performance found a significant association between elevated CNS readiness scores and improved countermovement jump performance (Heishman et al., 2018). An increase in power was also observed with increased CNS scores, which was hypothesized to be a result of greater motor unit recruitment and firing rate under a greater CNS readiness state (Dousset et al., 2007). NCAA Division 1 basketball players, underwent an Omegawave assessment upon entering the weight room, after which they performed a dynamic warm-up before moving straight into the countermovement jump tests. The finding that an athlete's CNS readiness score was positively correlated with the countermovement jump performance, a measure of neuromuscular performance (Alexiou & Coutts, 2008; Bosco et al., 1983; Wehbe et al., 2015; Welsh et al., 2008). These findings suggest that the Omegawave technology may be a useful tool to predict acute athletic performance.

Although HRV and Omegawave measurements have been examined as means of quantifying training load, managing adaptations to training, and even predicting performance, there is currently no literature examining the relationship between HRV measured by the Omegawave device and the effectiveness of a pre-competition training on sports performance. PAPE and pre-competition training has been shown to be effective tools for increasing performance (Bompa & Buzzichelli, 2015; Lagrange et al., 2020), but its application is highly dependent on the individual and there is no tool to accurately determine whether or not the athlete is suited for pre-competition training. The Omegawave device, based on its correlation to neuromuscular performance and ability to predict performance (Heishman et al., 2018), can potentially be a quick, non-invasive tool used to assess an athlete's HRV the morning of a competition to determine if a pre-competition training is appropriate to optimize their performance. Individualization of athletic training is one of the keys to maximizing performance. As world-renowned track and field coach, Dr. Anatoliy Bondarchuk, stated, "Everything that is *good* for one athlete can be *bad* for another"(Bondarchuk, 2015).

Chapter 3 - Methods

This study aimed to bridge the gap between HRV monitoring and the prescription of pre-competition training in ice hockey players. HRV has been shown to be related to athletic performance (Coyne et al., 2020; Peterson, 2018), however, its association with pre-competition training has yet to be examined. Therefore, the purpose of the study was to determine the relationship between an ice hockey player's HRV score on the morning of a game and the effect a resistance training session has on improving same-day on-ice performance. Considering it has been shown that females tend to have a higher baseline HRV than males (Koenig & Thayer, 2016; Ryan et al., 1994), a secondary aim of the study was to explore potential sex differences in the relationship between HRV and pre-game training.

3.1 Participants

Members of the McGill University men's and women's varsity ice hockey teams aged 18 years and over were recruited to participate in the study. 30 players participated in the study, consisting of players from the 2023-2024 season.

The eligibility criteria included: 1) Age 18 years or older, 2) member of a McGill University varsity ice hockey team, and 3) had no current or previous injury that restricted their participation in the study (ex. musculoskeletal injury, concussion, etc.).

Discussions occurred with the head coach of both McGill varsity hockey teams. Both coaches were enthusiastic to allow their athletes to participate in this study. Recruitment for the proposed study was done in person, following a McGill varsity hockey team practice during the pre-season training camp (August 2023). The aims of the study, methodology, and importance of the research were explained to the players. All players had the chance to ask for further details at the meeting or in private with the student researcher. The main recruiter was a graduate student researcher from Dr. Andersen's laboratory. Participation was voluntary, and there were no negative consequences to the players if they did not wish to participate in the study. Written informed consent was obtained from all players before any assessments took place.

During the experimental period (ex. between testing dates), if a participant suffered an injury and was unable to participate in the tests, the player was withdrawn from the study.

The study was approved by the Institutional Review Board at McGill University, and players were informed of the benefits and risks of participating in the study prior to signing an approved consent form.

3.2 Experimental Timeline

The study required the participants to be present on three separate days, for a total of four sessions, each lasting between 45 and 60 minutes in length. On the first day (Day 1), participants were asked to report to the lab between 8:00 and 10:00 for baseline measurements, including anthropometric measurements and an iDXA scan. If a recent iDXA scan was previously done for a fellow Master's student's research, the results from that scan were used. The iDXA scan was performed for the potential analysis of body composition and its relationship to the subject of pre-competition training. After the baseline assessment, participants reported to the weight room, where they underwent a 1-repetition maximum (1RM) estimation test for the Barbell (BB) Pin Squat. Participants were asked about their prior knowledge of PAPE, prior use of pre-competition training, as well as their habitual caffeine intake. Next, the height of the safety pins was set to allow a half-squat to be performed and recorded. Once the height was recorded, participants began the 1RM estimation test.

On Day 2, participants were asked to report to the McGill University, McConnell Arena for the baseline on-ice performance test. Prior to the test, each participant performed a baseline Omegawave test, which took approximately 4 to 5 minutes to complete. After a dynamic off-ice warm-up and five minutes to warm up on the ice, participants began the on-ice test. The test took approximately 2 minutes to complete.

On the last day (Day 3), between 4 and 7 days after the baseline on-ice test, participants were asked to report to the varsity weight room between 10:00 and 12:00 to undergo the pre-competition training. Before the training, a second Omegawave assessment was performed. Participants then underwent a 5-to-7-minute dynamic warm-up before proceeding to the BB Pin Squat warm-up. After the training session, participants were asked to report to the McConnel Arena 4 to 6 hours later to complete the same on-ice performance test. This time lapse mimics the day of an elite hockey player the day of a competition if they were to perform a pre-competition training session. A third and final Omegawave assessment was conducted prior to the participants performing their second on-ice test.

Figure 1.
Experimental Timeline.

DAY 1	DAY 2		DAY 3
			Omegawave Test Pre-Competition Training
Anthropometric Measurements	Baseline On-Ice Performance Test	4-7 Days	4-6hrs
1RM Estimation Test			
			Omegawave Test Post-Training On-Ice Performance Test

3.3 Anthropometric Measurements

The athlete’s height and weight were measured during the first study visit. The height was measured using a Seca 216 wall-mounted stadiometer and the weight was assessed to the nearest 10^{th} kilogram using a Seca 635 platform and bariatric scale (Seca, Birmingham, UK).

3.4 Whole and Regional Body Composition

An iDXA scan (GE Encore 11.20 scanner and software) was performed to provide estimates of whole body and regional (ex. arm, leg) body composition (ex. muscle mass, fat mass (%), bone density). The whole-body scan took approximately 7 minutes per athlete.

Data was used to further characterize the athlete, as well as for potential exploratory analysis looking at the relationship between regional muscle mass (ex. Lower limbs) and the variables being examined.

Tricia Deguire, another Masters student researcher in Dr. Ross Andersen’s lab, collaborated to use the same iDXA scan results for a sister study conducted over the same time period. This was done to reduce the amount of whole-body radiation exposure to the participants.

3.5 1RM Estimation Test

To standardize the training loads for the pre-competition training session, a 1RM estimation test was conducted for the BB Pin Squat. Following a 5-to-10-minute dynamic warm-up, participants completed sets of three repetitions on the BB Pin Squat, ensuring a two-second pause on the bottom, and progressively increasing the load. The load was pre-determined based on the sex of the participant and is depicted in Table 1. The velocity of the bar was measured using the Gym Aware linear positional transducer (GymAware, Mitchell, Australia) and noted for each participant at each prescribed weight (Sanchez-Medina L; Pallares JG, 2017). A 3-minute recovery period was taken between sets. To reduce the risk of injury, a threshold of 0.5 meters per second (m/s) velocity was set in place. Once a participant averaged 0.5m/s on their three repetitions, the test was terminated. If they achieved a velocity greater than 0.5m/s, they were allowed to progress to the next weight.

Table 1.
Loads used by male and female participants during the 1RM estimation test.

	Male	Female
Set 1	185	95
Set 2	225	115
Set 3	275	135
Set 4	315	155
Set 5	345	175

All loads are in pounds (lbs).

Each load and velocity were inputted into an Excel sheet and used to provide an estimation of their 1RM using the following equations. Equation 1.1 included the mean concentric velocity (MCV) of the load used to determine the estimated relative load (% of 1RM) for each weight and velocity (Sanchez-Medina L; Pallares JG, 2017). Equation 1.2 then used the estimated relative load and the weight used (absolute load) to estimate the 1RM. The estimation attained from the heaviest load was assigned to the participant. The 1RM load was then used to calculate each participant's pre-competition training warm-up and training loads, which corresponded to different percentages relative to their 1RM.

$$\text{Estimated Relative Load (\%)} = (-12.87 * \text{MCV}^2) - (46.31 * \text{MCV}) + 116.3$$

Equation 1.1 – Estimated Relative Load (% of 1RM).

$$\text{Estimated 1RM (lbs)} = (100 * \text{Absolute Load}) / \text{Estimated Relative Load}$$

Equation 1.2 – Estimated 1RM.

3.6 On-Ice Performance Test

The on-ice performance test consisted of 9 maximal effort sprints of 40 meters, with a 3-second recovery period in between sprints, which is a test used by many elite hockey teams (Lagrange et al., 2020). However, neither of the McGill varsity ice hockey teams had previously used this test. Each sprint was timed using the Brower Timing System timing gates (Brower Timing System, Utah, United States). Based on the sprint times, the following performance metrics were calculated (Equations 2.1-2.3): peak sprint velocity, average sprint velocity, and average sprint time. Peak sprint velocity reflects the fastest of the 9 sprints.

$$\text{Peak Sprint Velocity} = (40 \text{ meters}) \div (\text{Fastest Sprint Time, seconds})$$

Equation 2.1 – Peak Sprint Velocity

$$\text{Average Sprint Time} = (\Sigma \text{ Sprint Time, seconds}) \div 9$$

Equation 2.2 – Average Sprint Time

$$\text{Average Sprint Velocity} = (\Sigma \text{ Sprint Velocity, meters/second}) \div 9$$

Equation 2.3 – Average Sprint Velocity

3.7 Post-Activation Performance Enhancement

Following the on-ice performance test performed the evening of the pre-competition training, the percentage of PAPE, or performance enhancement, was calculated using Equation 3 (Scott et al., 2018). Performance was measured for both average and peak sprint velocity, as well as average sprint time. A percentage of greater than 0% indicated a positive, or potentiating, effect on performance; a percentage of 0% indicated no effect of the resistance training on performance; a percentage below 0% indicated a negative effect on on-ice performance. However, the opposite holds for the metric of average sprint time, as a percentage greater than 0% indicated the average sprint times were longer, implying a decline in performance.

% PAPE = ([(Performance following pre-competition training) ÷ Baseline Performance] x 100) – 100

Equation 3 – Percentage of Post-Activation Performance Enhancement (PAPE) (Scott et al., 2018)

3.8 Pre-Competition Training

The pre-competition training session was performed 4 to 6 hours before the participants post-training on-ice performance. The participants then underwent a 5-to-7-minute dynamic warm-up before proceeding to the BB Pin Squat warm-up. The specific warm-up involved performing the warm-up sets included in Table 2. After the specific warm-up was completed, participants began the pre-competition training. The training involved 5 repetitions of the BB Pin Squat with 85% of their estimated 1RM, with a 2-second pause on the safety pins, paired with 6 rebounding Squat Jumps. After the jumps were completed, participants took a 3-minute recovery period. The complex of BB Pin Squats and Squat Jumps was repeated for a total of 5 sets.

Table 2.
Warm-up and training percentages, as well as repetitions, used during the pre-competition training session.

	Sets	Repetitions	Percentage
Warm-Up	1	5	55%
	1	5	65%
	1	5	75%
Training	5	5	85%

Percentage of each participant's estimated 1RM.

3.9 Omegawave Test

An Omegawave (Omegawave, Espoo, Finland) test was performed to provide measurements of central nervous system readiness (Direct Current (DC) Potential), cardiac system readiness (Heart Rate Variability (HRV)), and an overall athlete readiness score. The test included an Electrocardiogram (ECG) chest strap, a sensor, and two electrodes (forehead and base of the thumb of their dominant hand). The test took approximately 4 minutes per person.

Before placement, the chest strap was sprayed with water to wet the two sensors on both sides of the strap. Participants also had an electrode placed on the base of their right thumb and another on the middle of their forehead. The wire was then connected to the two electrodes, as well as the chest sensor. The chest sensor was finally attached to the chest strap before asking the participant to lie down on a flat surface with the palms up. The participant was asked to relax and refrain from talking or moving until the completion of the assessment. Once the participant was ready, the test was initiated. Roughly 4 to 5 minutes later, when the assessment was complete, the participant then sat up and the wire was removed from the electrodes, the chest strap taken off and cleaned, and the disposable electrodes were discarded.

The specific metrics that the Omegawave test provided and that were included in the study were the RMSSD, SDNN, DC Potential, Heart Rate, and Athlete Readiness. Athlete readiness refers to the athlete's current functional state or readiness to physically perform. It is based on the cardiac and CNS readiness scores computed by the Omegawave device. RMSSD reflects the root mean square of successive differences and represents the time variability between each successive heartbeat, or RR intervals. SDNN is another HRV metric and refers to the standard deviation of NN (RR) intervals over time (Khazan, 2013). DC potential is defined as the "brain biopotentials within a frequency range that is lower than the EEG range (0 through 0.5 Hz)" (Fomin).

3.10 Heart Rate Variability Classification

Participants were categorized as having high or low morning HRV, prior to the pre-competition training session. Those considered to have high HRV were those with a RMSSD score of above 42ms, while those classified to have a low HRV were those with a score equal to or less than 42ms. This categorization was based on the finding that individuals had a mean RMSSD reading of 42ms (Nunan et al., 2010), therefore, 42ms was set as the border between high and low HRV.

3.11 Statistical Analysis

Data was collected and interpreted through propriety software and then analyzed using the statistical software SPSS (v. 28.0). For all statistical analyses, alpha was set to 0.05.

Independent *t*-tests were conducted to explore sex differences for each individual baseline metric. Repeated measures analysis of variance (ANOVA) was conducted to analyze the different Omegawave metrics over three different time points. The main effects of sex and time, as well as time-sex interactions, were explored for each individual metric. Bonferroni post-hoc analyses were performed in the event of a significant F-ratio.

When analyzing the different on-ice performance metrics, two separate independent *t*-tests were performed. The first one was exploring the sex difference in each individual metric at both time points (baseline and post-training). The second test was done exploring the sex difference in the absolute change for each metric, thus providing an effect of time. An independent *t*-test was also conducted to explore the sex differences in the change in RMSSD from baseline to post-training and from pre-training to post-training.

Finally, to determine whether there was a relationship between a participant's morning HRV and PAPE, a two-factor ANOVA was performed. The two factors were sex (Male, Female) and morning HRV (HIGH, LOW). The categorization of participants as having HIGH or LOW HRV was based on the finding that the mean RMSSD score of individuals is 42ms (Nunan et al., 2010); therefore, participants with a score less than or equal to 42ms were placed in the LOW group, while those with a score of greater than 42ms were placed in the HIGH group.

Pearson Product Moment Correlations were performed to determine the relationships among HRV classification and PAPE, and the association between an athlete's change in HRV and PAPE.

Chapter 4 – Manuscript

Heart Rate Variability as an indicator of pre-competition training effectiveness on increasing ice hockey performance.

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Running Head: Heart Rate Variability and Post-Activation Performance Enhancement

Formatted to be submitted to: *The Journal of Strength and Conditioning Research*

ABSTRACT

The purpose of the study was to determine whether measuring an ice hockey player's morning HRV was significantly related to on-ice post-activation performance enhancement (PAPE) following a morning conditioning activity (CA). Participants performed a training session consisting of 5 sets of 5 repetitions of BB Inertia Squats with 85% of their estimated 1-repetition maximum, paired with 6 rebounding squat jumps. An on-ice performance test was conducted at baseline and 4-6 hours post-resistance training. HRV was also measured prior to both performance tests, as well as prior to the morning training session. Participants were characterized as having a HIGH (RMSSD > 42ms) or LOW (RMSSD $\leq$ 42ms) HRV. A two-factor ANOVA was conducted to determine the effect of sex and HRV classification on PAPE ($p \leq 0.05$). The female participants experienced greater improvements in performance on all metrics (peak sprint velocity, mean sprint velocity, mean sprint time). Also, those classified as having a LOW HRV demonstrated significantly greater increases in performance compared to those with a HIGH HRV score. However, there no significant sex-by-HRV interactions were observed. These findings imply the potential benefits of monitoring an ice hockey player's morning HRV on the day of a competition. Strength and conditioning conditions working with collegiate hockey players may now have a means of identifying responders to pre-competition training.

Key Words: RMSSD, Potentiation, Sport performance, Resistance training, Sex differences

INTRODUCTION

Sports science and the different fields of research exploring potential ways of enhancing ice hockey performance have grown over the last few years (Bizzini, 2022; Martini et al., 2022; Ronnestad et al., 2021). Many organizations in the National Hockey League (NHL) now hire sports performance experts, nutritionists, and sports psychologists, as well as strength and conditioning coaches. Testing an athlete's physical abilities and in-season monitoring of stress and workloads are essential for enhancing a player's recovery and performance (Buchheit et al., 2013).

One new method of improving hockey performance is with resistance training to induce a post-activation performance enhancement (PAPE) effect (Lagrange et al., 2020). PAPE is regarded as the increase in voluntary performance following a conditioning activity (CA) such as resistance exercise (Blazevich & Babault, 2019). The underlying mechanisms of PAPE include the phosphorylation of the myosin regulatory light chain upon release of calcium from the sarcoplasmic reticulum (Tillin & Bishop, 2009), improved motoneuron excitability (Golas et al., 2016), and increased arousal levels (Schmidt et al., 2009). Many factors of the CA affect its efficacy on improving voluntary performance. For example, PAPE is correlated with the strength level of the athlete, in which it was shown that stronger individuals experience greater percentage increases in performance (Seitz & Haff, 2016; Wilson et al., 2013). Rest intervals between the CA and the performance assessment may also play a key role (Wilson et al., 2013). Finally, the intensity of the exercise, or the load relative to an individual's 1-repetition maximum (1RM), also contributes to PAPE. However, currently, there is no clear consensus regarding the optimal intensity, as some studies suggest high intensity (Chiu et al., 2003; Seitz & Haff, 2016; Seitz et al., 2016) and others suggest medium intensity loads (Smilios et al., 2005; Sotiropoulos et al., 2010; Wilson et al., 2013). What the prior literature on PAPE concludes is that the effects of a CA are highly individualized (Golas et al., 2016; Kobal et al., 2019) and that “coaches should identify which athletes respond to a CA” (Batista et al., 2011).

Heart rate variability (HRV) is recently becoming an important metric that is monitored by sport scientists and coaches. This assessment is being used to track levels of fatigue (Schmitt, Regnard, & Millet, 2015) and provide an objective measure of an athlete’s adaptability to exercise (Aubert et al., 2003). HRV measurements are a means of assessing the balance between the two branches of the autonomic nervous system (ANS) (Malmo & Shagass, 1948), the sympathetic (SNS) and parasympathetic (PNS) nervous systems. The most useful HRV metric for the world of sports performance is the root mean square of successive RR interval differences (RMSSD), as it can be quickly measured (5 minutes) and is related to performance changes (Da Silva et al., 2014). A higher RMSSD score is an indication of greater vagal tone, or PNS activity (Li et al., 2022). Prior research on HRV has examined its utility in tracking an athlete’s training (Kiviniemi et al., 2007), predict performance (Coyne et al., 2021; Mahinrad et al., 2016; Morgan et al., 2007; Peterson, 2019), and monitor an athlete’s progress or adaptation to the training (Hynynen et al., 2006; Pichot et al., 2000). Sex and age differences in HRV have also been examined, with females demonstrating higher HRV (Koenig & Thayer, 2016).

HRV has been shown to decrease during exercise as a result of increased SNS activity and a withdrawal of vagal activity (Borresen & Lambert, 2008). These effects may last for more than 24 hours if the activity intensity is high enough (Al Haddad et al., 2009; Kaikkonen et al., 2010; Stanley et al., 2013). For example, resistance exercise may shift the balance of the ANS by decreasing vagal activity (Heffernan et al., 2006). Other studies also observed the withdrawal of parasympathetic activity up to 90 minutes post-exercise using between 40-80% of the participant's 1-repetition maximum (Rezk et al., 2006; Teixeira et al., 2011). These findings demonstrate the change in HRV as a result of intense exercise.

Although prior research has examined the relationship between HRV and exercise, and HRV as a predictor of performance, to our knowledge there is currently no study examining the relationship between PAPE and HRV. More specifically, no study has explored whether an athlete's HRV is an indicator of the PAPE effect an athlete will experience from a CA. Therefore, the purpose of this study was to explore the connection between an ice hockey player's morning HRV and the performance change they experience following a pre-competition training session. Based on the prior HRV literature and the effect exercise has on HRV, it was hypothesized that individuals with a higher HRV the morning of a competition would benefit from resistance training, as the CA will act to lower their HRV. Also, we hypothesized that given males exhibit greater absolute strength than females (Bartolomei et al., 2021) and a greater PAPE effect is seen in stronger individuals, we felt that the male athletes would respond better to the CA. These findings may provide strength and conditioning coaches with an objective way of determining which of their athletes would respond better and ultimately a means of individualizing each athlete's preparation for competition.

METHODS

Experimental Approach to the Problem

Prior to the start of the ice hockey season, participants reported to the athletic facilities on three separate occasions. On the first day, baseline assessments were conducted, including a whole-body iDXA scan and a 1RM estimation test for the BB Pin Squat. A second day was required to get a baseline assessment of their on-ice performance. Finally, the third day included a pre-competition training session in the morning, followed by the same on-ice performance test 4 to 6 hours after the training session. An Omegawave test to measure different metrics of physiological readiness and HRV was conducted prior to the two on-ice tests and the resistance training session. All participants included in the study participated in all three days.

Subjects

Thirty subjects participated in the study, all of whom were ice hockey players for the 2023-2024 McGill University varsity teams. From the thirty participants, eighteen were males (age = 22.44 ± 0.36 years, height = 173.85 ± 10.29 cm, weight = 87.30 ± 1.70 kg) and twelve were females (age = 19.67 ± 0.28 years, height = 169.12 ± 1.23 cm, weight = 66.14 ± 1.87 kg). The Institutional Review Board of McGill University approved this protocol. All participants gave written informed consent to participate in the study prior to their involvement.

Procedures

Anthropometric and Body Composition Assessment. Height and weight were measured during the first study visit. The height was measured using a Seca 216 wall-mounted stadiometer and the weight was assessed to the nearest 10^{th} kilogram using a Seca 635 platform and bariatric scale (Seca, Birmingham, UK). Body composition was assessed using an An iDXA scan (GE Encore 11.20 scanner and software). The scan provided estimates of whole body and regional (ex. arm, leg) body composition (ex. muscle mass, fat mass (%), bone density). The whole-body scan took approximately 7 minutes per athlete.

On-Ice Performance Test. The on-ice performance test consisted of 9 maximal effort sprints of 40 meters, with a 3-second recovery period in between sprints, which is a test used by many elite hockey teams (Lagrange et al., 2020). Each sprint was timed using the Brower Timing System timing gates (Brower Timing System, Utah, United States). Based on the sprint times, the following performance metrics were calculated (Equations 1.1-1.3): peak sprint velocity, average sprint velocity, and average sprint time. Peak sprint velocity was recorded as the fastest of the 9 sprints.

$$\text{Peak Sprint Velocity} = (\text{40 meters}) \div (\text{Fastest Sprint Time, seconds})$$

Equation 1.1 – Peak Sprint Velocity

$$\text{Average Sprint Time} = (\Sigma\ \text{Sprint Time, seconds}) \div 9$$

Equation 1.2 – Average Sprint Time

$$\text{Average Sprint Velocity} = (\Sigma\ \text{Sprint Velocity, meters/second}) \div 9$$

Equation 1.3 – Average Sprint Velocity

1RM Estimation Test. On the first study visit, participants performed a 1-repetition maximum (1-RM) estimation test. A thorough dynamic warm-up was conducted prior to beginning the test. The exercise tested was the Barbell (BB) Pin Squat, which involves squatting a barbell down to a set of safety pins, and resting the barbell for 2 seconds on the pins before squatting the load back up. The loads for the test were predetermined for both male and female participants (Table 1). The mean concentric velocity (MCV) of the bar was measured using the Gym Aware linear positional transducer (GymAware, Mitchell, Australia) and noted for each participant at each prescribed weight (Sanchez-Medina L; Pallares JG, 2017). A 3-minute recovery period was taken between sets. To reduce the risk of injury, a threshold of 0.5 meters per second (m/s) velocity was set in place. Once a participant averaged 0.5m/s on their three repetitions, the test was terminated. If they achieved a velocity greater than 0.5m/s, they were allowed to progress to the next weight. Based on the load and MCV, an estimated relative load (% of 1RM), as well as an estimated 1RM (lbs), could be calculated (Equation 2.1-2.2).

$$\text{Estimated Relative Load (\%)} = (-12.87 * \text{MCV}^2) – (46.31 * \text{MCV}) + 116.3$$

Equation 2.1 – Estimated Relative Load (% of 1RM).

$$\text{Estimated 1RM (lbs)} = (100 * \text{Absolute Load}) / \text{Estimated Relative Load}$$

Equation 2.2 – Estimated 1RM.

Pre-Competition Training Session. The pre-competition training session was performed 4 to 6 hours prior to the second on-ice performance test. After a thorough dynamic warm-up, participants performed warm-up sets for the BB Pin Squat before beginning the session. The session included 5 repetitions of BB Pin Squats with 85% of their 1RM, paired with 6 rebounding jump squats. Following a 3-minute recovery period, participants repeated this pairing for a total of 5 sets. All warm-up and training percentages are depicted in Table 2.

Post-Activation Performance Enhancement. Post-activation performance enhancement (PAPE) was based on the two on-ice performance tests (baseline, post-training). All three metrics determined from the tests were examined. PAPE was calculated using Equation 3.

$$\text{\% PAPE} = ([(\text{Performance following pre-competition training}) \div \text{Baseline Performance}] \times 100) – 100$$

Equation 3 – Percentage of Post-Activation Performance Enhancement (PAPE) (Scott et al., 2018)

Omegawave Test. An Omegawave (Omegawave, Espoo, Finland) test was performed to provide measurements of athlete readiness, heart rate, RMSSD, SDNN, and DC Potential. The test included an Electrocardiogram (ECG) chest strap, a sensor, and two electrodes (forehead and base of the thumb of their dominant hand). Each test took approximately 4 minutes per person.

Before placement, the chest strap was sprayed with water to wet the two sensors on either end. Participants had an electrode placed on the base of their right thumb and another electrode on the middle of their forehead. The wire was then connected to the two electrodes, as well as the chest sensor. The chest sensor was finally attached to the chest strap before asking the participant to lie down on a flat surface with the palms up. The participant was asked to relax and refrain from talking or moving until the completion of the assessment. Once the participant was ready, the test was initiated. Roughly 4 to 5 minutes later, when the assessment was complete, the participant was allowed to sit up, in which the wire was removed from the electrodes, the chest strap taken off and cleaned, and the disposable electrodes discarded in the garbage.

HRV Classification. Participants were categorized as having HIGH or LOW HRV based on their RMSSD score prior to the pre-competition training session. LOW HRV corresponded to a score of 42 milliseconds (ms) or below, while a HIGH HRV corresponded to a score greater than 42ms based on the finding that the mean RMSSD of individuals was 42ms (Nunan et al., 2010).

Statistical Analysis

Data was collected and interpreted through propriety software and then analyzed using the statistical software SPSS (v. 28.0). Independent *t*-tests were conducted to explore sex-differences for each individual baseline metric. Repeated measures analysis of variance

(ANOVA) was conducted to explore the different Omegawave metrics at the three different time points. The main effects of sex and time, as well as time-by-sex interactions, were examined for each individual metric. Bonferroni post-hoc analyses were performed to measure differences between the different time points. When analyzing the different on-ice performance metrics, two separate independent *t*-tests were performed. The first one was exploring the sex difference in each individual metric at both time points (baseline and post-training). The second test was done exploring the sex difference in the absolute change for each metric, thus providing an effect of time. Finally, to determine whether there was a relationship between a participant's morning HRV, sex, and PAPE, a two-factor ANOVA was performed. The two factors were sex (Male, Female) and morning HRV (HIGH, LOW). Significance was set to an alpha level of 0.05 ($p \leq 0.05$) for all analyses. Pearson correlation analyses were performed to determine the correlation between HRV classification and PAPE, and the correlation between an athlete's change in HRV and PAPE.

Given the lack of female athletes participating in the present study, it is understood that the study was under-powered.

RESULTS

Independent *t*-tests were performed to compare the characteristics between male and female players (Table 3). Significant sex differences in age and weight were observed, but not in height. Male participants also had significantly lower body fat than the females, $t(27) = -5.63$, $p < 0.001$, as well as averaging 22.48 kg more fat-free mass than females, $t(27) = 12.89$, $p < 0.001$. The weights used during the resistance training session were also greater for the male athletes, $t(25.775) = 15.31$, $p < 0.001$, with the men averaging 168.19 pounds more than their female counterparts. The males also used a significantly greater load relative to their body weight, *t*(27)

= 9.00, p < 0.001, than the females. Finally, there were no sex differences observed in baseline HRV (RMSSD), baseline resting heart rate, or habitual caffeine intake.

Omegawave Tests. Athlete readiness refers to the athlete's current functional state or readiness to physically perform. It is based on the cardiac and CNS readiness scores culminated by the Omegawave device. RMSSD stands for the root mean square of successive differences and represents the time difference between each successive heartbeat, or NN intervals. SDNN is another HRV metric and refers to the standard deviation of NN intervals over time (Khazan, 2013). DC potential is defined as the "brain biopotentials within a frequency range that is lower than the EEG range (0 through 0.5 Hz) (Fomin).

A repeated measures ANOVA was conducted to explore the effects of sex, time, and the interaction effect between sex and time on the different metrics measured by the Omegawave device (Table 4). There was no significant effect of time on RMSSD, $F(2, 56) = 0.070$, $p = 0.932$, of sex, $F(1, 28) = 0.009$, $p = 0.925$, or an interaction effect, $F(2, 56) = 1.263$, $p = 0.291$.

With regards to the metric of heart rate, there was no significant effect of time on RMSSD, $F(2, 56) = 1.008$, $p = 0.371$, nor an interaction effect, $F(2, 56) = 0.862$, $p = 0.428$. However, there was an effect of sex, $F(1, 28) = 7.189$, $p = 0.012$, partial $\eta^2 = 0.204$, with females averaging a heart rate of 8.15 beats per minute faster than male participants

There was no significant effect of time, sex, nor an interaction effect for both SDNN and Athlete Readiness.

There was no significant effect of time on DC Potential, $F(2, 54) = 0.024$, $p = 0.977$, or of sex, $F(1, 27) = 0.3.078$, $p = 0.091$. Although, there was a significant time-by-sex interaction effect, $F(2, 54) = 3.714$, $p = 0.031$, partial $\eta^2 = 0.121$. Further post-hoc analysis using a

Bonferroni correction, the female participants had a significantly greater DC Potential score compared to the male participants with a mean difference of 11.746 ($p = 0.007$), at the post-training time point. There was also a significant mean difference in the scores of males between the pre-training and post-training time points (mean difference = 5.324, $p = 0.048$), with the average scores being higher at the pre-training time. Mean values are displayed in Table 4.

On-Ice Performance Test. The mean times for the three different on-ice metrics (average velocity, average sprint time, and peak velocity) for the male and female participants at baseline and post-training are illustrated in Table 5. An independent *t*-test was conducted to evaluate the differences in on-ice performance between males and females.

At baseline, there was a significant sex difference for the metrics of average velocity, $t(28) = 8.669$, $p < 0.001$, with the males averaging 0.829 m/s faster than the females. On average, the men also completed the sprints in 0.933 seconds faster than the females, $t(28) = -9.201$, $p < 0.001$. Finally, peak sprint velocity was significantly different between males and females, $t(20.729) = 5.403$, $p < 0.001$, during the baseline on-ice performance test.

During the post-training on-ice performance test, the average velocity attained by the male participants was, on average, 0.534 m/s faster than the females and is a significant difference, $t(28) = 6.401$, $p < 0.001$. Average sprint time, $t(28) = -6.823$, $p < 0.001$, and peak sprint velocity, $t(28) = 4.517$, $p < 0.001$, were significantly different between the males and females, with the males performing the sprints faster.

Changes in HRV and On-Ice Performance. Table 6 displays the sex differences in changing RMSSD (baseline vs. post-training and pre-training vs. post-training) and change in the on-ice performance metrics.

Independent t-tests found no difference in changes in HRV between males and females from baseline to post-training, $t(28) = 1.645$, $p = 0.111$, or between pre-training and post-training, $t(28) = 0.831$, $p = 0.413$. Examination of the correlation between change in HRV of the two time periods and changes in the different on-ice performance metrics was performed. A significant negative correlation, $r = -0.417$, $p = 0.022$, was found between the change in RMSSD from pre-training to post-training and the change in peak sprint velocity.

With regards to the change in peak velocity from baseline to post-training, sex differences were observed, $t(28) = -2.351$, $p < 0.026$, with the females demonstrating a 0.394 m/s greater increase compared to the males. Females also improved their average sprint time 0.277 seconds more than the male players, $t(28) = 4.126$, $p < 0.001$. Finally, there was a significant difference in the change between baseline and post-training on-ice performance for the metric of average sprint velocity, $t(26.998) = -4.295$, $p < 0.001$, with the females improving 0.238 m/s more than their male counterparts.

HRV Classification and PAPE. Participants were categorized as having a HIGH or LOW HRV score based on a study by (Nunan et al., 2010). According to the review, the mean RMSSD score for individuals is 42ms. Based on this finding, 42ms was used as a reference point as to whether the participants of this current study were considered to have a high or low morning HRV. The distribution of participants is seen in Table 7.

A total of seven participants (4 male, 3 female) were observed to have very high RMSSD scores (>110ms). However, omission of these participants in the analysis had no significant effect on the results and thus remained in the analysis.

A two-way ANOVA was conducted to assess the effects of sex and an athlete's morning RMSSD score on the percentage increase in on-ice performance (PAPE) following a pre-competition resistance training session. The means and standard deviations for male and female participants categorized as having HIGH or LOW RMSSD scores are depicted in Table 8.

There was a significant effect for sex, $F(1, 26) = 4.65$, $p = 0.04$, partial $\eta^2 = 0.152$, on peak velocity PAPE. Females, on average, experienced an increase in peak sprint velocity of 0.34m/s more than the male participants. However, there was no significant effect of morning HRV, nor an interaction effect between participant's HRV and sex, $F(1, 26) = 0.72$, $p = 0.401$, partial $\eta^2 = 0.027$.

For the metric of average sprint time PAPE, there was a significant effect for sex, $F(1, 26) = 11.411$, $p = 0.002$, partial $\eta^2 = 0.305$, and for HRV, $F(1, 26) = 6.555$, $p = 0.017$, partial $\eta^2 = 0.201$. An increase in sprint time indicates a decrease in performance. Males saw an increase in average sprint times of 0.23 seconds greater the females. With regards to the difference between HIGH and LOW HRV athletes, those categorized as having a HIGH morning RMSSD score experienced an increase in average sprint time of 0.16 seconds greater than those in the LOW HRV category. Based on a Pearson correlation analysis, a participant's classification was significantly correlated, r = -0.411, $p = 0.024$, with average sprint time PAPE. However, there was no significant HRV-sex interaction effect, $F(1, 26) = 2.293$, $p = 0.142$, partial $\eta^2 = 0.081$.

There was a significant effect for sex, $F(1, 26) = 11.732$, $p = 0.002$, partial $\eta^2 = 0.311$, and for HRV, $F(1, 26) = 4.827$, $p = 0.037$, partial $\eta^2 = 0.157$, on average sprint velocity PAPE. Females saw an increase in average sprint velocity of 0.19 m/s greater than the males, while those with a LOW morning HRV saw an increase of 0.13 m/s greater than those categorized as having a HIGH HRV. Pearson correlation determined a significant correlation, r = 0.368, $p =$

0.045, between a participant's HRV categorization and their average sprint velocity PAPE. However, there was no significant interaction effect between the participant's sex and their HRV score on their percentage increase in performance, $F(1, 26) = 2.539$, $p = 0.123$, partial $\eta^2 = 0.089$.

DISCUSSION

The study examined the relationship between an ice hockey player's morning HRV score (RMSSD) and PAPE. By measuring an athlete's on-ice performance test at baseline, then measuring their HRV and performing a resistance training session 4-6 hours prior to repeating the on-ice performance test, the presence of a relationship between HRV and PAPE can be uncovered.

A most important finding of the study was that, although the male participants performed better during the on-ice performance tests, the females experienced a greater response to the pre-competition training. The female athletes had significantly larger percentage changes and improvements for all the on-ice performance metrics (peak sprint velocity, average sprint time, average sprint velocity) in response to the resistance exercise the morning of testing (Figure 1). Considering PAPE is heavily influenced by an athlete's current strength level and muscle fiber distribution (Kilduff et al., 2007; Seitz et al., 2015; Wilson et al., 2013), it was hypothesized that males would show a greater PAPE effect because they have a greater level of absolute strength (Bartolomei et al., 2021). The male participants of this study were significantly stronger than the females, as demonstrated by the heavier training load used for the conditioning activity. However, the females demonstrated greater improvements in on-ice performance in response to the training compared to the males. A potential explanation of this finding could have been that the females were stronger relative to their body weight compared to the males, as it was suggested squatting above 1.75kg per kilogram of body weight resulted in a greater PAPE effect

(Seitz et al., 2014). However, the male participants possessed a greater level of both absolute and relative strength compared to the females, therefore, excluding strength level as an explanation for this finding.

Although the females saw greater improvements in performance, despite being relatively weaker than the males in this study, this difference in strength may still be a potential explanation. Both males and females used the same relative loads (85% of their estimated 1RM). However, prior evidence in the PAPE literature demonstrated that stronger athletes respond better to higher-intensity exercise (Golas et al., 2017). What this implies is that the training stimulus might not have been strong enough to elicit a potentiation effect for the males, while being an appropriate load for improving the performance of the female participants.

Another key finding in this study was that an athlete's HRV classification (HIGH vs. LOW) was significantly correlated with average sprint time and average sprint velocity PAPE, but not with peak sprint velocity PAPE (Figure 2). What was found specifically was that the participants characterized as having a low HRV (RMSSD $\leq$ 42ms) saw a significant improvement in performance as a result of the morning resistance training. For LOW HRV athletes, average sprint time decreased 2.429% and average sprint velocity increased 2.175% more than those classified as having a high morning HRV score. We had speculated that players with a high HRV score the morning of training and on-ice test would see greater improvements. This was based on the evidence that lower HRV scores were correlated with better performance (Coyne et al., 2021; Morgan et al., 2007) and that resistance training results in an increase in sympathetic arousal and a decrease in HRV (Kingsley & Figueroa, 2016); therefore, a training session for someone with a high HRV was thought to lower their RMSSD score and ultimately improve their performance. Further analysis was conducted examining the correlation between change in HRV from the training stimulus and PAPE. A significant negative correlation was found between change in HRV from pre-training to post-training and peak sprint velocity, but not between average sprint time nor average sprint velocity. This is interesting because peak sprint velocity was the only metric not affected by the participant's HRV classification. Lowering an athlete's HRV with resistance training may then be an important factor for improving peak sprint velocity, while on the other hand, an athlete's HRV categorization is a better indicator of their change in average performance over an entire hockey shift as a result of a pre-competition training session.

Although the research into the relationship between HRV and PAPE is still in its infancy stage and requires further investigation, this study provides valuable insight into the performance preparation of hockey players. First, it is evident that female hockey athletes may benefit from a resistance training session on the morning of a competition. The increase in average sprint time and average sprint velocity means they will have a higher chance of winning on-ice races for the puck or of getting in a better position defensively. A hockey shift is composed of many explosive sprints and not a single maximal sprint. What the findings of this study show is that pre-competition training can increase a female hockey player's speed throughout a whole shift rather than just their first couple of sprints.

This study also sheds light on the possibility of using and monitoring HRV as a means of indicating whether a hockey player should train the morning of a competition. Based on the results, athletes with an RMSSD score less than or equal to 42ms may respond better to pre-competition training compared to athletes with a score greater than 42ms. With the increasing accessibility of HRV monitors, daily monitoring may be a valuable tool for strength and conditioning coaches and sports performance specialists to better tailor a hockey player's preparation for competition.

Strengths of this investigation include the use of high-level collegiate hockey male and female players. Given the dearth of research on female hockey players, this study may offer important new insights into optimizing performance in female athletes. In addition, we used advanced, reliable equipment for HRV measurements, training load prescription, and on-ice performance testing. The Omegawave device has been shown to be a reliable, accurate tool for HRV measuring (Kalmetyev, 2009; Struganov, 2007), along with a measurement of DC Potential to compute an overall Athlete Readiness Score. The GymAware linear positional transducer device was also used to standardize the training loads for all the participants and has been shown to be a valid measure of barbell velocity (Weakley J, 2020).

One of the limitations of the study was the sub-optimal ice conditions for the on-ice testing, especially for the post-training on-ice performance test for the male participants. The study was conducted in late August and the outdoor temperature was high, which may have required additional work by the ice maintenance crew of McConnell Arena to ensure a suitable ice surface to skate on. The warm weather could have affected the on-ice performance of some of the male participants, as the hot weather renders the ice softer and may require greater muscular efforts from the participants. Another limitation is that the study was conducted just prior to the Fall school semester at McGill University, which is a time many of the student-athletes return back to campus and finalize their courses and living arrangements. This extra psychological stress of preparing for the semester may have influenced the participants' HRV measurements. There is limited research on the standard norms for high and low RMSSD scores, as individuals have their own unique norms, thus the classification of participants into

HIGH and LOW HRV based on a single value (42ms) may also have its limitations. Finally, we recognize that a limited sample size may have affected the interpretation of our findings.

Further investigation into the relationship between an athlete's HRV the morning of a competition and the effectiveness of pre-competition training is recommended. The investigation into the connection between an athlete's morning HRV and their response to different training intensity ranges (low vs. medium vs. high) can provide further information regarding the individualization of pre-competition training protocols. Further research may also examine multiple HRV "zones" (VERY HIGH, HIGH, MEDIUM, LOW) to determine an optimal HRV zone for prescribing pre-competition training.

PRACTICAL APPLICATIONS

The findings of this study may help strength and conditioning specialists objectively determine how to optimize their athletes' preparation for competition. The literature on PAPE is still inconclusive regarding an optimal training protocol, as the effects are highly dependent on the individual (Batista et al., 2011; Kobal et al., 2019). Therefore, these initial findings regarding the relationship between an athlete's morning HRV and the effectiveness of resistance training prior to performing may provide a way for coaches to determine which athletes would respond better on any given day.

This study also provides insight into the value resistance training has on PAPE in female hockey players. Although strength level is a factor in the effectiveness of resistance training on PAPE (Seitz et al., 2014), female hockey players who do not attain the strength standards may still see improvements in performance. Coaches working with female hockey players can use this evidence to further optimize their athletes' preparation for competition.

Finally, as HRV measuring devices become more accessible (ex. Whoop™), more collegiate and professional sports organizations can use these findings as a reason to monitor their athletes' morning HRV. Monitoring may potentially enable the coaches to further individualize their approaches to competition preparation, as they will have individualized standard RMSSD scores for each athlete. Thus, they obtain a better understanding if an athlete's HRV is high or low relative to their norm.

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ACKNOWLEDGEMENTS

The authors of the study would like to thank the players of both McGill University ice-hockey teams, as well as their coaches, for their time and participation. The authors of this investigation have no relationships with the companies or manufacturers mentioned. The results of the present study do not constitute an endorsement of the products by the authors or the NSCA.

Table 1.

Loads used by male and female participants during the 1RM estimation test.

	Male	Female
Set 1	185	95
Set 2	225	115
Set 3	275	135
Set 4	315	155
Set 5	345	175

All loads are in pounds (lbs).

Table 2.

Warm-up and training percentages, as well as repetitions, used during the pre-competition training session.

	Sets	Repetitions	Percentage
Warm-Up	1	5	55%
	1	5	65%
	1	5	75%
Training	5	5	85%

Percentage of each participant's estimated 1RM.

Table 3.

Characteristics (Mean ± SEM) of Male and Female Varsity Hockey Players.

	Male (n = 18)	Female (n = 12)	Total (n = 30)
Age (years)	22.44 ± 0.36	19.67 ± 0.28 *	21.33 ± 0.35
Height (cm)	173.85 ± 10.29	169.12 ± 1.23	171.96 ± 6.13
Body Weight (kg)	87.30 ± 1.70	66.14 ± 1.87 *	78.55 ± 2.33
Body Fat Percentage (%)	17.62 ± 0.76	26.23 ± 1.47 *	21.18 ± 1.09
Fat-Free Mass (kg)	68.88 ± 1.26	46.40 ± 1.05 *	59.58 ± 2.26
Baseline HRV	75.00 ± 12.74	83.25 ± 14.33	78.30 ± 9.43
Baseline Resting HR	61.50 ± 1.87	67.50 ± 2.46	63.90 ± 1.56
Caffeine Intake	1.25 ± 0.20	0.875 ± 0.31	1.10 ± 0.17
Training Weight (lbs)	340.28 ± 9.52	172.08 ± 5.49 *	273.00 ± 16.45
Relative Strength	4.59 ± 0.11	3.09 ± 0.12 *	3.96 ± 0.16
Position			
Forward	12	6	18
Defense	6	6	12

Relative Strength – 1RM divided by bodyweight (lbs/kg).

*Significantly different from male players ($p \le 0.05$).

Table 4.

Measurements (Mean ± SD) of Athlete Readiness, HRV, and DC Potential at Baseline On-Ice Testing, Pre-Training, and Post-Training On-Ice Testing.

	Male (n = 18)	Female (n = 12)	Total (n = 30)
Baseline On-Ice			
Athlete Readiness	4.67 ± 0.93	4.67 ± 1.06	4.67 ± 0.97
Heart Rate	61.50 ± 7.94	67.50 ± 8.51 *	63.90 ± 8.57
RMSSD	75.00 ± 54.10	83.25 ± 49.65	78.30 ± 51.63
SDNN	74.28 ± 36.23	86.83 ± 40.93	79.30 ± 38.00
DC Potential	12.07 ± 10.26	16.38 ± 13.59	13.80 ± 11.68
Pre-Training			
Athlete Readiness	4.76 ± 1.07	4.70 ± 1.35	4.73 ± 1.17
Heart Rate	57.89 ± 8.59	67.25 ± 10.31*	61.63 ± 10.26
RMSSD	78.17 ± 52.08	75.67 ± 50.90	77.17 ± 50.74
SDNN	79.83 ± 37.06	82.00 ± 40.49	80.70 ± 37.80
DC Potential	12.95 ± 11.39	14.44 ± 8.24	13.57 ± 10.07
Post-Training On -Ice			
Athlete Readiness	4.83 ± 1.23	4.46 ± 1.12	4.68 ± 1.18
Resting Heart Rate	59.50 ± 8.40	68.58 ± 12.52 *	63.13 ± 11.01
RMSSD	84.06 ± 59.14	73.00 ± 48.84	79.63 ± 54.64
SDNN	73.22 ± 34.82	80.42 ± 43.86	76.10 ± 38.12
DC Potential	7.63 ± 10.19 ‡	19.38 ± 11.22 †	12.49 ± 11.98

*Significant effect of sex ($p \le 0.05$).

†Significant effect of sex, only at post-training time point ($p \le 0.05$).

‡Significant difference between pre-training and post-training, only for male participants ($p \le 0.05$).

Table 5.

On-Ice Performance Metrics (Mean ± SD) at Baseline and Post-Training On-Ice Testing in Male and Female Varsity Hockey Players.

	Male (n = 18)	Female (n = 12)	Total (n = 30)
Baseline			
Peak Sprint Velocity (m/s)	7.09 ± 0.62	6.26 ± 0.17*	6.76 ± 0.64
Average Sprint Time (s)	6.51 ± 0.28	7.45 ± 0.25*	6.89 ± 0.54
Average Velocity (m/s)	6.20 ± 0.27	5.42 ± 0.18*	5.89 ± 0.45
Post-Training			
Peak Sprint Velocity (m/s)	6.93 ± 0.30	6.50 ± 0.18*	6.76 ± 0.33
Average Sprint Time (s)	6.60 ± 0.27	7.26 ± 0.24*	6.87 ± 0.41
Average Velocity (m/s)	6.10 ± 0.25	5.56 ± 0.17*	5.88 ± 0.35

*Significant effect of sex ($p \leq 0.05$).

Table 6.

Changes in HRV and On-Ice Performance Metrics (Means ± SD) in Male and Female Varsity Hockey Players.

	Male (n = 18)	Female (n = 12)	Total (n = 30)
Δ HRV (RMSSD)			
Baseline vs. Post	9.06 ± 31.08	-10.25 ± 32.15	1.33 ± 31.41
Pre vs. Post	5.89 ± 28.32	-2.67 ± 26.50	2.47 ± 27.47
Δ On-Ice Performance			
Peak Sprint Velocity (m/s)	-0.16 ± 0.57	0.23 ± 0.11*	-0.0023 ± 0.48
Average Sprint Time (s)	0.091 ± 0.19	-0.19 ± 0.17*	-0.02 ± 0.22
Average Velocity (m/s)	-0.10 ± 0.20	0.14 ± 0.11*	-0.0063 ± 0.20

*Significant difference between males and females ($p < 0.05$).

Table 7.

Number of Male and Female Players with High or Low HRV Scores.

	High	Low	Total
Male	13	5	18
Female	8	4	12
Total	21	9	30

High HRV – RMSSD > 42ms.
Low HRV – RMSSD ≤ 42ms.

Table 8.

On-Ice Performance PAPE (Mean ± SD) for Male and Female Participants Classified as Having High or Low HRV.

	High	Low	Total
Peak Sprint Velocity (%)			
Male	-2.31 ± 7.64	-0.38 ± 3.86	-1.77 ± 6.74
Female	4.36 ± 0.88	2.51 ± 2.45	3.74 ± 1.72 *
Total	0.23 ± 6.80	0.91 ± 3.46	0.44 ± 5.94
Average Sprint Time (%)			
Male	2.50 ± 2.68	-1.36 ± 1.39	1.43 ± 2.95
Female	-2.14 ± 2.52	-3.13 ± 1.29	-2.47 ± 2.18 *
Total	0.73 ± 3.45	-2.15 ± 1.57 †	-0.13 ± 3.27
Average Velocity (%)			
Male	-2.62 ± 2.97	1.13 ± 1.43	-1.58 ± 3.12
Female	2.35 ± 2.22	2.95 ± 1.59	2.55 ± 1.98 *
Total	-0.73 ± 3.62	1.94 ± 1.70 †	0.07 ± 3.38

High HRV – RMSSD > 42ms.
Low HRV – RMSSD ≤ 42ms.
*Significant effect of sex ($p < 0.05$).
†Significant effect of HRV ($p < 0.05$).

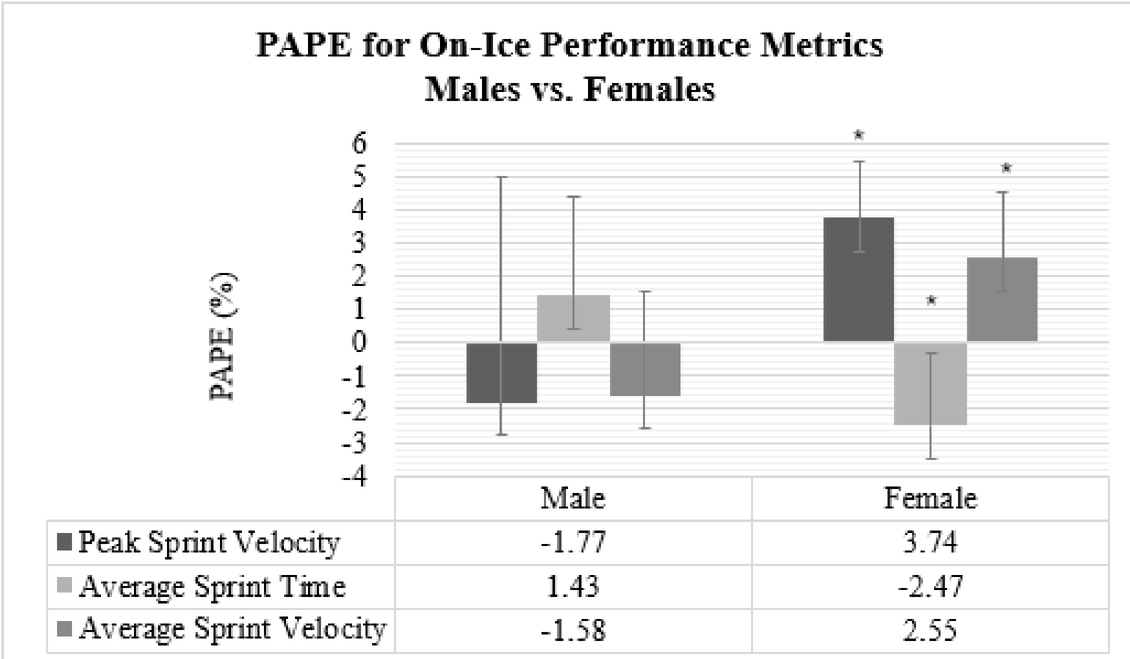

Figure 1. On-Ice Performance Metrics PAPE (%) for Male and Female Varsity Hockey Players.

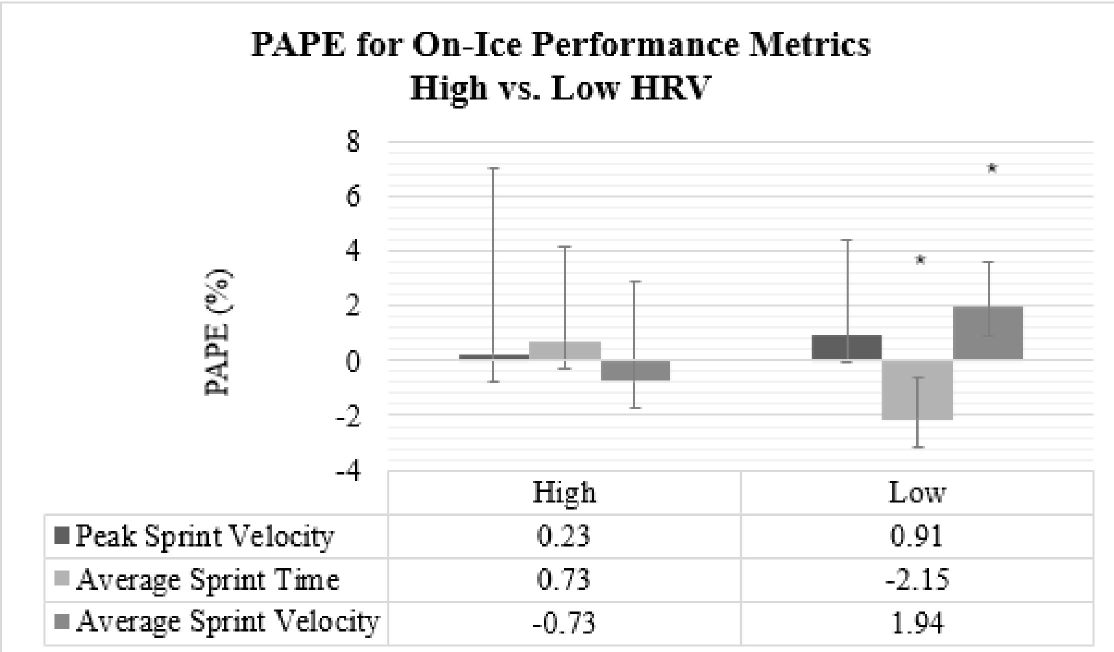

Figure 2. On-Ice Performance Metrics PAPE (%) for Players Classified as Having High or Low HRV Scores.

Chapter 5 – Summary, Conclusion, Recommendations, and Practical Application

6.1 Summary

The purpose of the present study was to explore the relationship between an ice hockey player's morning HRV score and their change in on-ice performance following a pre-competition training session. It was also the goal of the study to determine if there was a sex difference in PAPE and in the relationship between HRV and PAPE. Two on-ice performance tests were performed, with the second session completed 4 to 6 hours after a resistance training session. A baseline assessment of anthropometric measurements, a DXA scan, and an Omegawave test were done on the first day.

Thirty players (n = 30) from the 2023-2024 McGill University men's and women's varsity ice hockey teams participated in the study. All participants were older than 18 years of age and had no prior or current injury that prevented their involvement. The participants completed the baseline assessments, including a 1RM estimation test, and the pre-competition training session before the second on-ice performance test. Omegawave tests were performed prior to the baseline on-ice test, the training session, and the post-training on-ice test to provide multiple HRV scores (RMSSD, SDNN) and athlete readiness scores.

The first hypothesis of the study was that athletes with a greater HRV score (HIGH) prior to the training session would experience greater improvements in on-ice performance than those with a lower HRV score. The hypothesis was tested by collapsing the participants into one of two categories based on their morning HRV. Those classified as HIGH HRV had an RMSSD score greater than 42ms, while those put in the LOW HRV group had an RMSSD score less than or equal to 42ms. Based on the results, participants categorized as having a low morning HRV saw significant improvements in average sprint time and average sprint velocity. The athletes part of the HIGH group saw an increase in average sprint time of 0.16 seconds greater than those of the LOW group, while the LOW group had an increase in average sprint velocity of 0.13 m/s greater than the HIGH group. Further analysis indicated an athlete's HRV categorization had a significant negative correlation (r= -0.411) with average sprint time and a significant positive correlation (r = 0.368) with average sprint velocity, indicating that LOW HRV was correlated with greater improvements in both performance metrics. However, there was no effect of HRV classification on peak sprint velocity PAPE, nor an HRV-sex interaction effect for either of the three performance metrics.

The finding that LOW morning HVR was correlated with increased performance is in accordance with the prior literature (Coyne et al., 2021). However, it also contradicts many studies that state a higher HRV should be desired by athletes (Buchheit et al., 2010; Pichot et al., 2000). The reason for this contradiction may lie in the purpose of the study. Many of the prior studies examined recovery and adaptations to training, but the purpose of this study was to examine the relationship HRV has with performance. Lower HRV was previously associated with ameliorated performances, possibly because of the positive effects increased sympathetic activation has on mental and muscular performance.

The second hypothesis of the study was that there would be a sex difference in PAPE and the relationship between HRV and PAPE, specifically that male athletes would experience a greater increase in performance. Although the males performed better than the females on the sprints, the females experienced a significantly greater increase in performance. The female participants improved their peak sprint velocity 0.34 m/s and their average sprint velocity 0.19 m/s more than the male participants. The males also experienced an increase in average sprint time 0.23

seconds greater than the females, indicating a decline in performance. It is thought that the results were found because of the training intensity utilized. Previous research examining the relationship between an athlete's strength level and PAPE concluded that stronger individuals responded better to high intensity (>90% of 1RM), whereas weaker individuals responded better to lower-intensity training (Golas et al., 2017). Therefore, the intensity and load prescribed for the female participants may have been optimal for their strength level, but the intensity for the males, who were stronger than the females, might have been too low to elicit a PAPE effect. What this means for the strength coach working with male and female hockey players is that they must test for absolute and relative strength to determine the optimal loading parameters for a pre-competition training session.

6.2 Conclusion

Within the delimitations and limitations of the research project, the following conclusions are:

1) The female participants experienced a larger, positive increase in all on-ice performance metrics from the pre-competition training session. This was demonstrated by the increase in peak sprint velocity, decrease in average sprint time, and increase in average sprint velocity compared to baseline.
2) Participants classified as having LOW HRV (RMSSD $\leq$ 42ms) prior to the morning resistance training session experienced significantly greater improvements in on-ice performance for the metrics of average sprint time and average sprint velocity.
3) There was no interaction between the participant's sex and their HRV categorization on their response (PAPE) to the pre-competition training.

4) Change in RMSSD from pre-training to before the post-training on-ice test was negatively correlated with a change in peak sprint velocity.

6.3 Recommendations

Based on the findings of the present study, the following recommendations are:

1) Considering there is not much information regarding RMSSD score norms, future research into HRV should start examining if there is a mean or standard RMSSD score among individuals or groups of individuals (ex. Males vs. females, professional vs. recreational athletes).
2) Follow-up studies should explore the relationship between HRV and PAPE in the context of different sports, such as basketball, soccer, and rugby, as previous research has found performance-enhancing effects of resistance training in many sports.
3) Further exploration into the connection between an athlete's morning HRV and their response to pre-competition training should investigate different RMSSD score ranges, rather than categorizing athletes into one of two groups.
4) Future studies should examine how athletes of different RMSSD scores respond to different training intensity (% of 1RM) ranges.
5) Due to the large time gap between the resistance training session and the competition, further examination must be made in the individual responses to training at different times prior to competition (ex. 4 hours vs. 6 hours vs. 8 hours) and the relationship morning HRV has on the different responses.

6.4 Practical Application

Professional ice hockey players and organizations are continuously exploring different ways to enhance their performance during the competitive season. Resistance training prior to a competition may improve performance by inducing a PAPE effect. However, the responses are highly dependent on the individual, requiring strength and conditioning coaches to obtain a means of determining which athletes will benefit from the training. The findings of the present study can provide valuable insight into an objective way of determining whether an ice hockey player will benefit from a PAPE-inducing resistance training session the morning of a competition.

HRV monitoring devices are becoming more popular and accessible to athletes (ex. Whoop). With this increased monitoring, strength and conditioning coaches can track and use their athlete's data to objectively decide how to optimally prepare the athlete prior to a game. Although this study was conducted on team sport athletes (ice hockey), the findings could prove to be valuable in an individual sport setting. For example, track and field athletes, such as 100m sprinters, compete fewer times throughout the year than team sport athletes, but must be optimally prepared for competition. Pre-competition training may be very effective for improving sprinting performance. Therefore, by objectively monitoring an athlete's readiness through HRV assessments, a sprint coach can individualize each athlete's approach. The data obtained from the monitoring may permit the coach to determine whether to include resistance training the morning of a race to optimize their athlete's performance.

Finally, there is minimal literature on the effects of pre-competition training on female ice hockey players. As the present study importantly concluded, that female ice-hockey players can also benefit from resistance training before performing. These findings should be considered by strength and conditioning coaches working with female ice hockey players as a means of potentially enhancing their players' on-ice performance.

Appendix A. Informed consent form approved by the McGill University IRB

Department of Kinesiology & Physical Education
475 Pine Avenue West
Montreal, Quebec, H2W 1S4
Phone: 514-398-4184

RESEARCH PARTICIPANT INFORMED CONSENT

Protocol Title: HRV as an indicator of pre-competition training effectiveness on increasing ice hockey performance.

Sponsor:	McGill University
Primary Investigators:	Ross Andersen, Ph.D.
Research Assistant:	Maximilian Daigle, B. Sc; Tricia Deguire, B. Ed (PE)
Date:	December 21, 2022

Introduction

You are being invited to take part in a pilot research study because you are a member of the McGill Redbirds or Martlets Varsity Hockey Team. This research participant informed consent form explains the research study and the role you will play in the study. Please read it carefully and take as much time as you need. Please ask questions at any time about anything you do not understand.

Purpose of the Study

The purpose of this pilot study is to examine the relationship between an athlete's heart rate variability (HRV), often a marker of their physical readiness, and the effectiveness of a pre-competition training on improving athletic performance for male and female ice hockey players. The investigators aim to determine if there is in fact a relationship between HRV and sport performance, primarily seen in changes in sport performance after a morning training compared to baseline measurements.

Procedures

If you agree to partake in this study, you will be asked to participate in three study visits, split into three separate days, which will take place at the Health and Fitness Promotion Laboratory and the McConnell ice hockey arena. The first and third testing days will be separated by one week. All visits will last between 45 and 60 minutes. On the first day, you will undergo baseline assessments. The following day, you will perform a 1-repetition estimation test. On the third day, you will report to the laboratory for a HRV measurement and a 45-minute strength training session. Later that day (4-6 hours later), you will report to the McConnell Arena to perform the same HRV test and the on-ice performance assessment.

Baseline assessments include:

1) Body Composition Assessment

You will be asked to complete a full body DEXA scan, which typically takes between 5 to 10 minutes. You are required to lie on your back and remain still, to the best of your ability, for the duration of the scan. Height and weight will be measured before hand. From the scan, different whole and regional body composition measurements will be obtained (fat tissue mass, lean tissue mass, and bone density). Body composition measurements will be shared with Tricia Deguire's study as a way to prevent overexposure to radiation from the iDXA scan.

2) Omegawave Test

The Omegawave Test involves wearing a chest strap with an ECG monitor, as well as an electrode on both your forehead and the base of your dominant hand's thumb. You will be asked to lay on a flat surface and to remain relaxed with your arms to your side and your legs uncrossed. The duration of the test is approximately 4-minutes. From the test, your heart rate variability (HRV) will be measured.

3) 1-Repetition Maximum (1RM) Estimation

With the use of device that measures the velocity of a barbell, you will be performing sets of 3 repetitions for the BB Pin Squat. The velocity of the bar is measured and noted. The weight is progressively increased until you attain an average velocity of 0.5m/s. The loads are pre-determined for both male and female participants. Based on the velocity, an estimation of your 1RM can be conducted.

4) On-Ice Performance Test

The on-ice performance test involves 9 sprints of 40 meters with a 3-second break, which is just about long enough to turn around and get set at the new starting line. Your sprint times will be measured by the Brower Timing Systems timing gates. The following will be measured and calculated: average sprint velocity, average sprint time, fastest sprint velocity, and fastest sprint time.

Sprint Velocity (meters/second) = (40 meters) ÷ (Fastest Sprint Time, seconds)

A short resistance training workout will be completed 4 to 6 hours before your on-ice testing on the second day. The strength training session will include a dynamic warm up (ex. jump rope, high knees, etc.) before performing 5 sets of 5 reps of Barbell Pin Squats paired with 6 squat jumps. There will be a 3-minute rest period between each set of squats and jumps. The weight on the barbell will be dictated by the speed of the movement, measured by the GymAware speed device. The training session will look as follows:

1) 5- to 10-minute dynamic warm up
2) Barbell Pin Squat Warm Up

   1 x 5 x 55%; 1 x 5 x 65%; 1 x 5 x 75%

3) Training Session

A1) Barbell Pin Squats	-	x 5 (85% of 1RM)	-	10 second rest
A2) Squat Jumps	-	x 6	-	3 minutes rest

   Repeat for total of 5 sets

Prior to the resistance training session, you will complete the Omegawave HRV assessment. The test involves you wearing an electrocardiogram (ECG) strap around your ribcage and placing two electrodes, one on the forehead and the other on the base of your dominant hand's thumb, that connects to a sensory attached to the strap. You will be asked to lay flat on your back and refrain from moving and talking while the device measures your HRV. The length of the test is approximately 4-minutes.

To summarize, the study visits will look as follows:

Day 1 – Baseline Tests

- Body Composition Assessment
- Omega-Wave Test
- On-Ice Performance Test

Day 2 – 1RM Estimation Test

Day 3 – Testing Day (5-7 days after Day 1)

- 10:00 – 12:00 am
  - Omega-Wave Test
  - Strength Training Session
- 4:00 – 6:00 pm
  - Omega-Wave Test
  - On-Ice Performance Test

Potential Risks, Harms, or Discomforts

Body Composition Assessment: You will receive a small dose of radiation from the body composition scans. The radiation exposure from participating in this study is equivalent to a whole-body exposure of 0.3 mrems in total because each scan represents a whole-body exposure of 0.3 mrems. Naturally occurring radiation (cosmic radiation, radon, etc.) produces whole body radiation exposures of about 300 mrems per year. An average chest x-ray is 10 mrems.

Strength Training Session: There is always a potential risk with resistance exercise. However, the risk has been taken into consideration and precautions are in place to prevent any possible injury. The safety pins in the squat rack will be placed at a height so that, in the case of the weight being too heavy and failure to complete the repetition, the bar may be placed back on the safety pins, and you can safely remove yourself from the weight. Also, the weight of the squat will be determined by the speed of the movement and will fall in the "heavy" range, but not maximal. Therefore, if the speed of the movement becomes too slow, which increases the risk of injury, the weight will be decreased to ensure the right speed is attained and thus, the risk of injury reduced. This activity is similar to exercises you do in off-ice training in the weight room.

On-Ice Performance Test: Being that the sprints performed during the tests are maximal efforts, along with being done on an ice surface, there is always a risk of potential injury in cases such as a malfunction in equipment or poor ice conditions the moment of testing.

If you believe you have suffered an injury as a result of your participation in the study, you should contact Maximilian Daigle at (514) 755-8732 or Dr. Ross Andersen at (514) 398-4440 ext 0578.

Benefits

You will receive an in-depth analysis of your Omegawave testing results, DEXA body composition assessment, and of how well you performed during the on-ice testing. The results of the study may ultimately provide information how to individualize training protocols to maximize performance in elite hockey players. More specifically, your individual results will be explained in a way that allows you to optimize your own performance and give you a competitive advantage over your opponents.

In Case of Injury

Every precaution will be taken to ensure your safety and wellbeing during the study. If you suffer an injury as a result of your participation in this study, you will receive appropriate medical care under your Quebec Medicare or private insurance plan.

Voluntary Participation/Withdrawal

Participation in this study is completely voluntary. You, as the participant, may decline to participate in any testing or may withdraw at any moment under your own will. Declining to participate or withdrawing from the study will not result in any loss of benefit (ex. loss of playing time). If you decide to withdraw from the study, your data will be removed from the study, unless given permission to keep.

Is there any cost to be in this study?

There is no cost to you for participating in this study. You will not be charged or billed for any costs of the procedures used.

Compensation

No monetary compensation will be given for participating in this study.

Confidentiality

Personal information to be gathered include **full name and email address.** Each participant will also be coded with an ID number (ex. 01, 02, 03, etc.). However, personal information and identification will not be made public and will be stored on a document saved onto a password protected USB key. The only people who will have access to the USB key and knowledge of the password will be the researchers involved with the study. The data will be stored securely for seven years after the scientific reports on this study are published, as per University policy. A member of the McGill Institutional Review Board, or a person designated by the IRB, may access the study data to verify the ethical conduct of the study.

Dissemination of Results

The pooled results will be published in academic research articles, as well as in both academic and personal presentations on the subject of the study. In addition, individual results will be explained to each respective participant. Coaches will have the opportunity to be explained the aggregated results of the study in the debriefing meeting following the conclusion of the study. The intention of explaining the results is to potentially provide valuable information on how you as an individual should prepare before competition to attain peak performance.

Contact

If you have any questions or would like clarifications about the project, please contact the following:

Maximilian Daigle (MSc. Exercise Physiology, McGill University)

maximilian.daigle@mail.mcgill.ca

(514) 755-8732

OR

Dr. Ross Andersen (Department of Kinesiology and Physical Education, McGill University)

ross.andersen@mcgill.ca

(514) 398-4440 (extension 0578)

If you have any questions about your rights as a research participant, or wish to submit a complaint or ethical concern, please contact **Ms. Ilde Lepore**, Ethics Officer, McGill Institutional Review Board at: 514-398-8302 or ilde.lepore@mcgill.ca.

I have read this consent form and the information provided about this study. I have had the opportunity to ask any questions I may have. I am aware that participation in this study is voluntary and that I may withdraw my consent at any time. I do not give up any of my legal rights by agreeing to take part in this study. A copy of the signed and dated consent form will be provided to me. I consent to take part in this study.

____

Name of Participant (Please Print)

____

Signature of Participant Date

____

Name of Person Obtaining Consent (Please Print)

____

Signature of Person Obtaining Consent Date

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