Are there exercise volume and intensity differences between soccer athletes on the same team?

By

Brett Armstrong

Submitted in partial fulfilment of the requirements

For the degree of Master of Science

at

Dalhousie University

Halifax, Nova Scotia

August 2025

Dalhousie University is located in M'kma'ki, the

Ancestral and unceded territory of the Mi'kmaq

We are all Treaty people

Table of Contents

List of Tables

List of Figures

Abstract

Collegiate student athletes must balance their academic responsibilities with rigorous game, practice, and strength training schedules making it difficult for coaches to monitor athlete's weekly exercise volume and intensity. Therefore, the purpose of this research was to implement a global navigation satellite system (GNSS) to monitor athletes and examine the potential differences in exercise volume and intensity that may exist within a Canadian university soccer program. In year I significant differences between athlete categories were identified for measures of total cumulative distance (m), high-speed running distance (HSR-D: m), rate of high-speed running (R-HSR: m/min). In year II a successful training intervention, based on year I outcomes, increased TD (m), HSR-D (m), R-HSR (m/min) measures for supporter athletes which decreased the training differences between starters and low-minute athletes. This research project successfully implemented a GNSS and developed an intervention that reduced exercise volume and intensity differences between the athlete categories through structured tracking and training opportunities.

List of Abbreviations Used

GPS	Global Positioning Systems
GNSS	Global Navigation Satellite Systems
IMU	Inertial Measurement Units
m/min	Metres per Minute
NCAA	National Collegiate Athletic Association
FIFA	Federation Internationale de Football Association
HSR-D (m)	High-Speed Running Distance (m)
R-HSR (m/min)	Rate of High-Speed Running (m/min)
MAS	Max Aerobic Speed
NDC	National Development Centre
NSL	Northern Super League
m/s	Metres per Second
Km/hr	Kilometers per Hour
WCS	Worst Case Scenarios
Hz	Hertz
HDOP	Horizontal Dilution of Precision
ICC	Intra-class Correlation Coefficient
CV%	Coefficient Variation Percentage
RMSE	Root Mean Square Error
SE	Standard Error
ME	Mean Error
TEE	Typical Error of the Estimate
VIFT	Final Velocity
MSS	Max Sprint Speed
TD	Total Distance

AIC	Akaike Information Criterion
BIC	Bayesian Information Criterion
LME	Linear Mixed Effect
TP	Training Period
MD	Mean Difference

Acknowledgements

I would like to express my gratitude and appreciation to my supervisor, Dr. Ryan Frayne for his continued mentorship and guidance. Your support for me as an undergraduate student, young professional, and now graduate student has been invaluable in propelling me through a challenging, but extremely rewarding transition back to academics. Thank you for your kindness, and for always valuing my input as a student and professional. This lab and group of students has allowed me to grow creatively; you have enabled me to be confident and approach problems with curiosity and excitement. I will be forever grateful for your mentorship.

A huge thank you to everyone in the BENlab, my lab mates Dylan Sutherland and Jessica Reddin for your assistance, guidance in write club, and friendly day to day shared experience. To Brett Feltmate, Sophie Inkpen, and Aidan Nolan thank you for your support through the ups and downs of the academic year. To Seth Daley, thank you for always being kind, thank you for always having an open door and for your help with everything from coding to teaching. Your patience, generosity, and genuine excitement to help me with my own work has been life changing. To Dr. Jeff Zahavich, thank you for your continued support and belief in me as a young professional and student. I am forever grateful for our daily catch ups, your positivity, guidance, and support.

Lastly, I would like to extend my gratitude to my friends, family, and colleagues for their support and guidance over the course of my academic journey. Thank you to Cindy Tye and Tim Maloney for their continued support, and for building an athletic department that has encouraged me to grow and continue to learn every day. A heartfelt thank you to my fiancé, who has supported me not only through the long, busy coaching days but throughout this entire project. Your guidance and belief in me have been incredibly important throughout my career.

Chapter 1: Introduction

1.1 Introduction

Collegiate student athletes must balance their academic responsibilities with rigorous game, practice, and strength training schedules. In Canadian University sports, the lack of technology and available personnel make it difficult to track potential differences in exercise volume and intensity between high-minute (starters) and low-minute (finishers/supporters) athletes. Also, student athletes balancing academic course loads may struggle to properly rest and recover from their workouts, and as a result these athletes may be susceptible to injury from overuse and/or sudden increases or decreases in activity (1). For example, in professional soccer, one particular study reported that poor exercise management accounted for 42% of illnesses and 40% of injuries (2) which could be explained by preceding spikes in match play or mismanaged training volume and intensity.

Soccer games are played over 90-minutes and interspersed with intermittent high intensity running actions including accelerations, and decelerations through moments of offensive and defensive on-ball and off-ball play (3). The potential for injuries makes it imperative to track these high physical demands. Quantitative assessments of exercise volume and intensity is commonly used to manage an athlete's exercise exposure. Tracking exercise can be done internally (i.e. an athlete's body response to exercise) and externally (i.e. the work completed by an athlete) (1). Internal exercise tracking can be collected with ratings of perceived exertion or physiologically through heart rate monitors, blood lactate measures, etc. External exercise tracking is typically accomplished through temporal measures of exercise (timing), distances travelled during exercise, movement velocities and accelerations, etc. (1,4,5). Tracking athletes external exercise is highly beneficial when designing training interventions and making decisions on game play.

In soccer, athlete exercise monitoring is often quantified using global navigation satellite systems (GNSS) and inertial measurement units (IMU) (2,4–18). GPS tracks athlete positional data over time to calculate athlete distance travelled and movement velocity (4). Inertial measurement units measure acceleration and decelerations of an athlete and can provide change of direction magnitudes (in G forces) (9). Therefore, GPS and IMUs permit the direct measurement of a soccer players' external exercise during matches and practices (18) by quantifying player velocity and categorizing the gameplay using velocity zones to evaluate absolute (professional and international standards) and relative (individual performance standards) measures of training intensity (9–24).

GPS athlete exercise data can be further separated into exercise volume and measures of intensity. Exercise volume is often reported as total (cumulative) distance, total high-speed running distance, total acceleration and deceleration distance (explosive distance), and total high metabolic load distance (distance run above max aerobic speed) (7,8,19,22,25). Measures of exercise intensity are often reported as play above high intensity running thresholds defined through high-speed running zones and represented by work rates (distance/time); including total session velocity (m/min), time within specific high-speed running zones, and time spent above high-speed running thresholds (7,8,19,22,25). Monitoring exercise volume and intensity allows a coach and/or sport scientist to identify if an athlete is training at high or low levels and identify when there are sudden changes in exercise exposures.

GPS has been used in soccer at the professional, international, and NCAA level. Doyle et al. (2022) used GPS to track position, velocity, and distance in international women's soccer play and identified that the total distance covered during matches were between 8 km to 11 km, at a 10.1 km average (10,11,26). NCAA women's soccer show similar full match demands for Division I-III with total match volumes of 8.8 - 9.8 km (7,10). Movement intensities, measured in average velocity, for international and professional soccer were 105 – 113 m/min for top finishing FIFA 2015- and 2019-Women's World Cup teams (27). However, it remains to be identified how exercise volume and intensity may vary across high game exposure athletes (starters), and those athletes with low game exposure (finisher and supporter groupings).

Some elite soccer programs define their athletes as starters, finishers, and supporters. Starters receive the most amount of game minutes, finishers receive some game minutes, while supporters typically do not play in the games. According to Bortnik et al. 2023, starters are exposed to peak locomotor demands and high velocity transition play measured as distance travelled above high-speed running thresholds (i.e. high speed running distance: HSR-D (m)) and the distance travelled per minute above high-speed running thresholds (i.e. Rate of High-speed running: R-HSR (m/min)) (22,28). Starters often have increased amounts of exercise volume and intensity, specifically time above max aerobic speed zones (MAS) (23,28–30), and this group also receives the greatest exposure to tactical game planning through training, and competitive game play (23). There are often large discrepancies in training for finishers and supporters from week to week because of their decreased game exposures; athletes in these roles may also miss exercise/tactical top-up support which limits their athlete development (23,28–30). There is a need for a greater understanding of exercise volume and intensity, and tactical exposure differences between these athlete groups (22,31) so that the finishers and supporters can be trained up to the physical and tactical demands of a starter.

At the Canadian University Sport level there has been one study to date regarding the use of GPS and exercise exposures (32); however, this research did not address athletic exposure differences between starters, finishers and supporter athlete categories. Therefore, there remains a need to identify how the in-game and practice demands (both exercise and tactical) differ across athlete categories, because the high demands on student athletes often results in finishers, and supporters moving up to starting roles without proper preparation. These increases in athlete role can be abrupt leaving the finisher and supporter athletes susceptible to injury (1,33).

The primary purpose of this research was to implement a GNSS and integrative IMU athlete tracking system to quantify and determine exercise volume and intensity differences between high-minute (starters) and low-minute athletes (finishers and supporters) over two seasons. The secondary objective of this research was to identify if there were any tactical exposure differences between starter, finisher, and supporter athletes. It was hypothesized that there would be discrepancies between the three athlete groups in exercise volume and intensity, with starters having the largest volume and intensity compared to finishers and supporters in season one. It was hypothesized that, in season two with the addition of an intervention to minimize any identified athletic exposure differences, that there would be no differences in exercise volume, intensity, and tactical exposure between the three athlete categories.

Chapter 2: Literature Review

2.1 Overview of Soccer

Soccer is a sport where two teams play in a 90-minute match, split into two 45-minute halves. In the case of injury delays, stoppage time may be added to the end of games. Each team has 11 players on the field which is divided into four position groupings: forwards, midfield, defenders, and goal keepers. These positions have both general and assigned specific roles in accordance with their tactical responsibilities (22,31) and can be substituted in and out of the game at any time, which may result in different physical performance demands between positions.

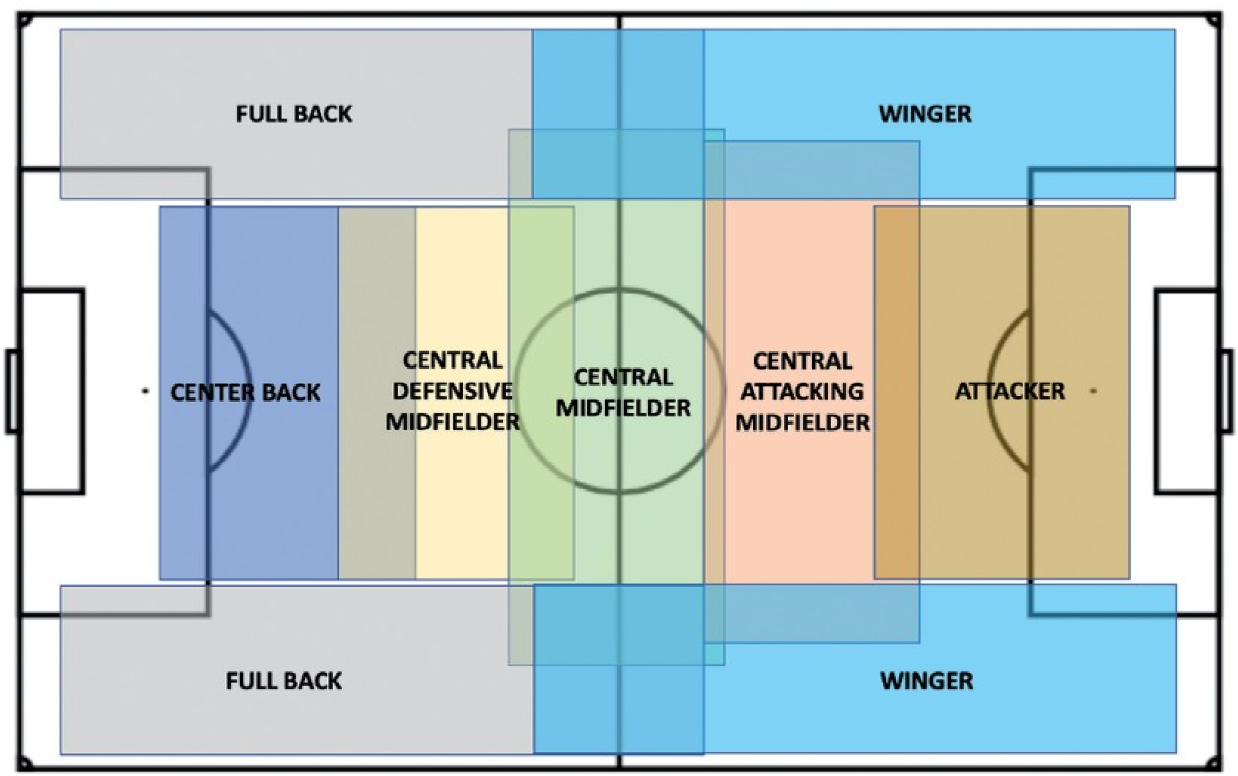


Figure 1 General and specialized tactical roles on game analysis from Aalbert and Van Haaren (2019). Forwards represent the 'attacking' side of the diagram (Right), as winger, and attacker position; defenders represent the 'backfield' (left) in right and left fullbacks, and center back positions; midfielders represent central defensive, central, and attacking midfield positions.

All soccer players are required to jump, kick, tackle, turn, sprint, change their pace and sustain forceful contacts while maintaining balance and control during on and off-ball competition (3). These physical demands can occur on either the offensive or defensive side of the ball, with all athletes being required to compete at varying levels of intensity (22). Defending and off-ball attacking involve athletes tracking the play to maintain position and cover large distances at moderate to low intensities to sustain strong tactical and technical presence (3,34). High-intensity actions typically occur when athletes compete for ball possession and when they attempt to maintain control of the ball against defensive pressures. High intensity bouts can also occur during offensive and defensive transitions, and through organized team tactics (22,28). The frequency at which an athlete experiences high-intensity bouts of exercise are multifaceted; however, their position on the field and whether they are a starter or finisher are two factors that will heavily impact their exercise volume, intensity, and tactical demands (22,28).

2.1.1 Canada Soccer Development Pathway

In Canada, soccer is subdivided into provincial organizations with each province structuring athlete development through sanctioned clubs. The athlete experience at high performing clubs can be variable between clubs and is different from that of the National Development Centre (NDC). NDC programs are federally funded and centralize the best youth soccer athletes in Canada. These centres provide high performing youth athletes with National Team level resources including independent sports science, therapy team staff, and coaching to deliver year-round support. NDC athletes are also exposed to more competitive national and international match play compared to top-tier club teams and receive continued support through individual development plans written by national team coaches. Different from the NDC pathway, top-tier club level, program delivery is sanctioned by the club and funded through player fees. Each sanctioned club manages their own coaching and performance standards in accordance with Soccer Canada's Long Term Athlete Development Model (35). Top tier club programs uphold Canada Soccer's mandate to employ registered coaches who are qualified to work with kids and deliver coaching principles designed by Canada Soccer. The top-tier club pathway provides a parallel pathway to the NDC for athletes pursuing competitive collegiate soccer or professional opportunities through a privatized model.

The newly developed professional women's Northern Super Leage (NSL) and the Quebec and British Columbia NDC programs now operate outside of government funding and are designated professional academies. Professional academies adopt the European professional model where professional soccer organizations have a senior women's team and tiered age category development groups. Academy and NDC seasons are year-round and structured through 12-month competitive seasons that are led by full time Canada Soccer staff who design and implement the Canada Soccer Long Term Athlete Development model. Youth athletes competing at the academies and NDC level are high targets for national team recruitment, international professional academies, and NCAA programs. However, few will become national team members. At the Canadian U-Sports level, few athletes will experience the structure and consistency of the integrated support teams that are provided at academies and NDC programs. Most incoming U-Sports athletes are high performing athletes competing for local top-tier club organizations.

2.2 Athlete Exercise Volume and Intensity Tracking

Coaches and Sports Performance professionals engage in athlete monitoring and the measurement of training to decrease injuries, but it is also to gain a competitive edge. In preparation for their competition, athletes are put through systematic training that causes stress on muscular, metabolic, cardiovascular, and neurological systems (36). Training in professional sport is demanding and as a result can cause delayed onset fatigue, reductions in power output, increases in internal measures of stress response, and potentially an injury. Measurement of the dose – response relationship has been very easily evaluated in laboratory settings; however, due to logistical challenges in sport it is not always feasible to evaluate athletes in a lab or through extensive test batteries (36). Metabolic testing, and physiological performance measurements have had a significant role in quantifying athlete performance, but with considerable time constraints these tests can be difficult to administer. As a result, it is difficult to understand the cause-and-effect relationships in training when resources are spent evaluating physiological adaptions in a non-sport specific environment. However, technology in sport has evolved to the point where athletic performance can be evaluated during training and game play.

2.2.1 Tracking External Exercise Volume and Intensity in Soccer

Gabbett et al. 2016, emphasizes the importance of integrative research for athlete monitoring to inform coaching decisions, and 'ownership' of the injury process for the athlete support team (i.e. coaches and staff) involved in supporting athlete health and overall team success (1,33). The coaching staff benefit from an understanding of the physical demands of competition and the drills that make up the week of preparation for games (33). Quantifying training and match play allows sports performance staff, coaches, and athletes to visualize the training process, and prevent training errors leading to improved performance (1,33). It can also be used for coaches to identify any differences between the roles of all 'players' (e.g. high-minute, and low-minute athletes). Coaches can obtain measures of athlete's exercise volume and intensity metrics in training and in matches from the use of global navigation satellite systems (GPS) and inertial measurement units (IMU).

2.2.2 Inertial Measuring Units

Inertial measurement units' (IMU) contain tri-axial accelerometers, gyroscopes, and magnetometers. IMUs' permit the measurement of position, velocity, and can help predict measures of impact or reaction forces, and various physical load estimates dependent on proprietary filtering and coding specific to the manufacturer (37). In sport, IMU's are often used to quantify athlete acceleration and deceleration and change of direction magnitudes (37). IMU's integrated with Global Navigation Satellite Systems (GNSS) are used to obtain smoother movement trajectories and reduce random measurement error following processing (37).

2.2.3 Global Positioning Systems and Global Navigation Satellite Systems

Global Positioning Systems (GPS) and Global Navigation Satellite Systems (GNSS) track athlete positional and time data to calculate distance and velocity in outdoor sports (4). Integrated GPS, GNSS and IMUs permit the direct measurement of a soccer players' external match and practice demands (25). GPS have a lower sampling rate than IMUs and can be limited by the number of satellites that can view the device during data collection. GNSS devices are capable of tracking multiple satellite constellations in devices with 10 Hz sampling rates. Obtaining GNSS signals with a greater number of satellite constellations produces greater inter-unit and intra-unit reliability and reduces an error known as horizontal dilution of precision Horizontal dilution of precision (HDOP) indicates the device drift when a user is stationary or in resting position; therefore, these devices require validation before being implemented with a team (38–40).

Validation research has associated increased sampling frequencies with an increased accuracy of GPS and GNSS technology. While this is confirmed in devices with sampling frequencies ranging from 1 – 5 Hz compared to 10 Hz, there have been limited meaningful differences between 18 Hz and 10 Hz devices (41). GPS, GNSS, and integrated IMU's in sport performance have emphasized the importance of sampling rates of greater then 10 Hz to minimise distance measurement error, for the use of specific velocity zone-based measures, peak velocity, and position. Augmented GNSS and GPS signals have also proven to improve device accuracy for GNSS chipset quality because it broadcasts to a greater number of satellite constellations which reduces horizontal dilution (41).

GPS/GNSS, have become common high standard for tracking soccer athletes. These systems can provide coaches, sport scientists and researchers with consistent and accurate measures of athlete exercise volume and intensity (1,37). Through standardized training evaluations, data can be leveraged to inform practice strategy, athlete management, and improve athlete performance. GPS/GNSS and IMU's permit comparison of match play averages within and between athletes but also allow coaches to reduce player development errors (33). External exercise tracking can be done many ways, but typically in soccer it is quantified by measuring the athletes distance travelled, movement velocity, and acceleration/deceleration (7). External exercise tracking can also be separated into exercise volume and measures of intensity. Exercise volume is often reported as total (cumulative) distance, total high-speed running distance, total acceleration and deceleration distance (explosive distance), and total high metabolic distance (distance run above max aerobic speed) (8–10). Measures of exercise intensity are often reported as rates of play above high intensity running thresholds (R-HSR: m/min); including total session velocity (m/min), high-speed running zones, and time spent above high-speed running thresholds

(8–10); which can be used to classify an athlete's performance and their maximum sustainable training volume and intensity (11).

While GNSS on its own does not reduce injury, the use of GNSS by practitioners and coaching teams use the objective data to periodize training volume and intensity, which has proven to reduce injury incidence (42). Specifically, global navigation satellite systems can aid in helping support staff reduce athlete injury through: quantifying targeted increases in exercise volume and intensity (42,43), track the physical demands during time of injury (43), track and measure external load and the tactical demands of match play (11,27,28), and to help quantify and manage reinjury risk in return to play (1,8,33,34). Continued research in soccer has also allowed practitioners to quantify match play, training and high intensity periods preparing athletes for the worst-case scenarios (WCS) in sport.

2.2.4 GPS, GNSS, and IMU integration

Categorization of multi-directional movement in team sports with intermittent exercise is extremely common (18,26); therefore, GPS/GNSS systems are commonly integrated with an IMU to measure accelerations in three planar axes (37). Integrated IMU's have sampling rates at 100 Hz and are used to autodetect high frequency sport-specific events. IMU's assist in interpolating signal processing algorithms in periods of high acceleration and deceleration, where increases in sampling frequency are required to calculate changes in instantaneous speed (37); However, not all GPS, GNSS, with integrated IMU's have undergone enough rigorous validation to uphold the same accuracy standards as GPS and GNSS measures of locomotor patterns which include the use of position, distance, velocity zones, and instantaneous velocity (38–40). GPS/GNSS systems are produced for both commercial and research applications that produce a multitude of metrics for consumers. Therefore, when using GPS/GNSS systems in team sports, the use of rigorously tested metrics and 10 Hz GNSS sensors are crucial in conducting reliable and valid volume and intensity measurements for soccer athletes.

2.2.5 Exercise Volume Demands

The physical demands of soccer competition have been evaluated at the international, professional and collegiate level. Exercise volume is often reported as total (cumulative) distance, and measures of zone-based distances determined through velocity thresholds including HSR-D (m), sprint distance, and distance covered at low-speed running zones (1,22,25). An analysis of international women's soccer identified total in-game distance through 90 minutes to be 9389 +/- 368 m (25), these outcomes are similar to other studies reporting total distance averages of 8 km to 11 km, with a 10.1 km average per match (10,25,26). These values are similar to NCAA Division I – III athletes that averaged a total distance of 8.8 km and 9.9 km per game (7,10) and the Canadian University women's game, which averaged 8.8 – 9.8 km (32).

In professional soccer high speed running can be based on absolute velocity zones established through international standards. At the international women's level, high-speed running distance is quantified when an athlete runs > 15.6 km/hr, which ranges between 911 – 1,063 m per game. Sprint distances are quantified when and athlete runs > 20 km/hr, which ranges between 223 – 307 m per game (20). Furtado Mesa et al. 2023, used absolute velocity zones for high-minute versus low-minute athlete research. These velocity zones were designed to align with professional women's soccer and are 0 – 13.99 km/hr for low-speed running, 14 – 19.99 km/hr for high-speed running, and > 20 km/hr for sprinting. However, differences in absolute velocity zones between athletes and at different levels of play mean that absolute running zones are only relevant to international women's soccer; Therefore, an alternative solution may be the use of athlete relative velocity zones. According to Kavanagh et al. (2023), there is a strong positive correlation (r = .9) between maximal aerobic speed (MAS) and an individual's velocity at maximum oxygen consumption. The use of MAS to set relative velocity zones allows for measures of training intensity that "provide appropriate contextual training prescription" (19) at an individual level (2,4,5,7,20,25).

2.2.6 Exercise Intensity Demands

Soccer research often focuses on the average demands of competition, resulting in athletes being underprepared for the most extreme periods of high intensity play, which is known as the worst-case scenarios in sports (WCS) (28). Measures of exercise intensity capture periods of high intensity play and are often reported as play above high intensity running thresholds, demonstrating an athlete's ability to sustain highly competitive work rates. These periods are represented by average velocities and are measured in metres per minute (m/min). Average movement velocities (m/min) per game or training session can be subdivided into thresholds, predetermined from relative high-speed running zones and time spent above maximum aerobic speed MAS (zone 5: defined as max aerobic speed running threshold) and tagged as the rate of high-speed running (R-HSR: m/min) (19,44). Exercise intensities for international and professional soccer measured average movement velocities between 105 and 113 m/min in top finishing FIFA 2015- and 2019-Women's World Cups, with bottom finishing teams having average movement velocities between 86 – 94 m/min (27). Similar movement velocities were observed in the women's NCAA game at 100 – 110 m/min (18,32).

Exercise intensities are also represented through movement rates (m/min), measuring rate of high-speed running (R-HSR: m/min) above high-speed running thresholds during games or training sessions. Exercise intensities for R-HSR (m/min) at the international and professional soccer level are: high speed running > 15.6 km/hr with work rates ranging between 10.1–11.8

m/min, and sprinting > 20 km/hr (m/min) range between 2.5–3.4 m/min per game or training session (20,27). High speed running bouts or MAS running are defined as short time periods of work rates that are 1.5 - 2.0 times full match velocity values at 24.6 – 47.4 m/min and have been quantified in the NCAA to be 166 – 270 m/min for full match average movement velocities (33,44). Currently there is no literature on Canadian University women's soccer that classifies average movement velocity (m/min) and rates of high-speed running (m/min) (27). Therefore, there remains a need for better Canadian University women soccer exercise intensity analysis with a focus on individual athlete differences.

2.2.7 High-minute versus Low-minute Athletes

There remains concern in team sport that there are discrepancies in exercise volume and intensity exposures between high-minute and low minute athletes. For example, in professional men's soccer for both training and games, total distance, high-speed running distance, sprint distance and average movement velocity (m/min) were significantly different between high-minute and low-minute athletes (28). According to Bortnik et al. 2023, there were significant differences between high-minute and low-minute athletes in generating maximal acceleration and decelerations, as well as the rate of acceleration and deceleration (m/min). Lower-minute athletes have also been identified to have lower peak physical demands experienced and had fewer opportunities to reach maximal running outputs throughout the season, despite experiencing high exercise volume and intensity during the pre-season and in-season training (23,30). These differences in physical demands may be the result of low-minute athletes entering games during less intense periods of play (33). The large discrepancy in game play leaves low-minute athletes susceptible to training volume and intensity mismanagement, possibly resulting in injuries. In addition, poorly planned top-ups and periods of overload through congested periods of practice leading into games are cause for injury risk and poor performance adaptions (3,23,30,33).

Management of high-minute athletes is also extremely important for maintaining competitive upper limits in training and maintaining components of physical fitness. Starters are exposed to periods of maximum exercise intensity through frequent on ball and transitional play (3,28,30). High-minute athletes compete with greater in-game physical demands but also experience more congested tactical game play than low-minute athletes (3,23,30).

NCAA Collegiate women's soccer has one study evaluating measures of volume and intensity differences between high-minute and low-minute athletes (23). Both high-minute and low-minute athletes accumulated similar levels of exercise volume and intensity during practices (23); however, significant differences were observed in match's and seasonal totals, with low-minute athletes running significantly lower distances (31% average difference), lower high-speed distances (distance covered over high-speed threshold - 63% average difference), and a lower number of sprints (34% average difference) compared to high-minute athletes (23). High-minute athletes also had greater low-zone acceleration volumes, contributing to significant accumulation in acceleration counts and distance compared to low-minute athletes (finishers and supporters) (23).

2.2.8 Tactical Categorization in Soccer

Poor management of tactical training leads to performance deficits in the finisher and supporter (low-minute athlete) groups, while overtraining starters (high-minute athletes) who already experience peak physical demands. Athlete management is a shared process across medical, sports performance staff, and the coaching team to build collaborative practice plans (i.e. drill selection) that are informed from athlete tracking through both physical and tactical exposures. For example, using small sided games in practices that "adequately reflect/overload in game play scenarios like worst case scenario (WCS)" (28), while "running-based drills could be utilized as an effective strategy to minimize discrepancies between training and match play peak demands, especially in terms of high-speed and sprinting exposure" (28). Also, understanding the effect of substitution pattens in-games and the cost of training high-velocity tactical activities in high-minute athletes is important for coaches, the medical team, and sports performance professionals (28,29,45).

Categorizing tactical drills and establishing communication streams for the coaching staff and support team is crucial for reducing preventable injuries that occur due to training errors (22,28,33). Research currently evaluating drill classification in soccer, that quantifies physical and tactical outcomes, only occurs in a small subset of professional athletics (20). Therefore, there is a need to evaluate tactical drills and the effect that different drills have on measures of exercise volume and intensity, including high-speed running distance HSR-D (m) and rate of high-speed running meters per minute R-HSR (m/min) in collegiate women's soccer (19). At the professional and university level medical staff and the coaching team all impact playing time and participation. Physical and tactical alignment in research improves communication for the support team in professional athletics but also emphasizes the importance for study replication for programs with variation in playing standards, competition level, age, and sex.

2.3 StatSports Validity and Reliability

StatSports has three validated Apex GPS and GNSS models, the Apex Pro Series, Apex Team Series, and the Viper model. The Apex Pro model has the most advanced GPS and software package with an 18 Hz GPS, 10 Hz augmented GNSS, and integrated 952 Hz IMU. While the second model is a 10 Hz augmented GNSS and 952 Hz integrated IMU, both devices use the same hardware for broadcasting and processing signals with the advanced models only difference including the 18 Hz GPS and an updated software package. The Team Series model and software provides a feasible and validated team system for professional sports. StatSports Apex Team Series GNSS inter-unit reliability was calculated using intra-class correlation coefficients (ICC) and Coefficient variation percentage (CV%) during 30-meter sprints evaluating instantaneous velocity at 5–10 m, 10–15 m, 15–20 m, and 20–30 m (46). Across 436 trials, the ICC's were 0.96 at 5-10 m distances, 0.95 at 10 – 15 m, 0.95 at 15 – 20 m, 0.97 at 20-30 m, and 0.99 at 5 – 30 m. The CV% was 2.91% across 5-10 m distances, 2.18% at 10 – 15 m, 2.01% at 15 – 20 m, 1.64% at 20-30 m, and 1.85% at 5 – 30 m. The StatSports Apex Team Series system also had excellent instantaneous velocity and peak velocity reliability throughout the sprints (46). Due to market availability previous StatSports models have been more thoroughly researched compared to newer Apex models. However, the current Apex Team Series models include chipset hardware and data processing updates on the older third tier StatSport models (46,47). Recent comparison of the newer GNSS systems to older third tier GNSS units (10 Hz GPS, 100 Hz accelerometer) confirm improvements in Apex system inter-unit reliability and validity for the measurement of velocity, submaximal speed increase and decrease speed conditions (46,47).

Studies have also analyzed the validity between StatSports tracking systems (10 Hz GNSS Apex Team Series, and the 18 Hz GPS with 10 Hz GNSS Apex system). The StatSports Apex systems 18 Hz and 10 Hz were assessed for criterion validity against a 400 m running track, 128.5 m circuit, and 20 m sprint (41,48). Test-retest reliability was completed one week after the initial testing sessions and identified that the Apex 10 Hz GNSS device had a coefficient variation percentage (CV%) for the 400 m distance of 1.05 +/- 0.87%, 2.3 +/- 1.1% for the 128.5

m circuit and 1.11 +/- 0.99% for the 20 m sprint (41) compared to the criterion distance. In the second round of test-retest reliability, the 18 Hz GPS with 10 Hz GNSS Apex system had a CV% of 1.17 +/- 0.73% for 400 m distance, 2.11 +/- 1.06% for 128.5 m circuit, and 1.15 +/- 1.23% for 20 m distance (41). The two systems have extremely similar distance estimation scores, indicating that despite missing the 18 Hz GPS capability, the 10 Hz GNSS on its own produced accurate distance travelled estimations across repeated days of testing.

Tests measuring instantaneous velocity for the 18 Hz GPS with 10 Hz GNSS and the 10 Hz GNSS Apex units were determined to be 26.5 ± 2.3 km/h and 26.5 ± 2.6 km/h, respectively (41). These values were very similar to the criterion radar velocity measurement of 26.3 ± 2.4 km/h, resulting in no significant difference between measurements (41).

Crang et al. (2024) conducted further updated reliability and validity testing on the StatSports Apex 10 Hz GNSS model and an industry leading Catapult Vector S7 model (38). Straight line sprints and changing of pace were measured at 40 m during three trials. Change of pace was described as speeding up and slowing down over straight line 40m distance, while change of direction was measured through maximal 10 m acceleration and decelerations over a 40 m course. Across test re-test days for data collection, satellites ranged from 15 to 19 for Catapult and 21 to 23 for StatSports, with a horizontal dilution of precision (HDOP) of 0.5 to 0.6 for Catapult and 0.4 for StatSports. Root mean square error (RMSE) was used to determine the magnitude of difference between criterion measure in 1000Hz laser timing gates for instantaneous speed. Statistical analysis included peak speed, acceleration and deceleration using mean error (ME) 95% CI, and typical error of the estimate (TEE) 95% CI. The Apex System validity was recorded as (ME = 0.26, TEE = 0.10) for velocity (m/s), (ME = -0.39, TEE = 0.33) for acceleration (m/s^2), (ME = -1.2, TEE = -0.35), and (ME = 0.7, TEE = 0.27) for change of pace. Measures of instantaneous velocity and acceleration produced the largest StatSports RMSE which ranged from 0.14 to 0.17 m/s for speed (p = 0.29 to 1.00) and 0.22 to 0.43 m/s^2 for acceleration (p = 0.13 to 0.99), and Catapult at 0.12 to 0.21 m/s for speed (p = 0.001 to 0.85) and 0.26 to 0.47 m/s^2 for acceleration (p = 0.001 to 0.85). The largest RMSE for StatSports Apex 10 Hz GNSS in instantaneous velocity and acceleration was 'clinically small'. The StatSports Apex 10 Hz GNSS sensors provide valid measures of instantaneous velocity, instantaneous acceleration, peak velocity, peak acceleration, and measures of distance in sprinting and change of pace movements and are recommended for testing MAS (38); therefore, they are a recommended tool to use when tracking soccer athlete exercise volume and intensity.

2.4 Research Problem

Current research in women's soccer outlines match demands within professional women's soccer, at the national team level, and in NCAA collegiate athletics; however, it has been suggested that only 15% of all published research in soccer is on elite women's soccer (49). Within that pool of research, there remains a limited number of studies looking at effects of low-minute (finishers and supporters) and high-minute game play athletes (starters) on their exercise volume and intensity. To date only one study has implemented GPS, GNSS, and integrated IMU's in Canadian University Women's sport (32), and no studies have conducted longitudinal testing. This is problematic because the research on high level women's soccer may not directly apply to Canadian University athletics because of skill and experience level, and there may be different athlete development pathways in Canada compared to the NCAA and international levels. Therefore, conducting this research with GNSS and integrated IMU in a Canadian University athletic population improves the athlete development pathway in low-minute groups working towards achieving high-minute starting roles.

2.5 Purpose

The primary purpose of this research was to implement a GNSS and integrative IMU athlete tracking system to quantify and determine potential exercise volume and intensity differences between high-minute (starters) and low-minute athletes (finishers and supporters). The secondary purpose was to identify if there were any tactical exposure differences that occur between starter, finisher, and supporter athletes.

This research occurred in two phases, over two Dalhousie University Women's soccer team seasons (2023-2024, and 204-2025). Phase one of the project (2023-2024 soccer season) required piloting the use of a new GNSS and integrated IMU athlete tracking system to quantify and determine if there were exercise volume and intensity differences between high-minute (starters) and low-minute (finishers and supporters) athletes. It was hypothesized that there would be discrepancies between the three athlete groups in exercise volume and intensity, with starters having the largest volume and intensity compared to finishers and supporters.

Phase two of the project (2024-2025) implemented a training intervention based on the results of phase 1. The training intervention aimed to decrease exercise volume and intensity differences, and to identify if there are any tactical exposure differences between athlete categories. The GNSS and IMU system tracked exercise volume and intensity and assisted in tracking tactical exposures bi-weekly throughout the season to determine if the intervention reduced athletic and tactical exposure discrepancies. It was hypothesized that in year two of the project there would be a reduced discrepancy in exercise volume, intensity, and tactical exposure differences between the three athlete categories.

Chapter 3: Methodology

3.1 Participants and Recruitment

All recruited athletes were from the Dalhousie University Women's Soccer team. This study tracked twenty-four (n = 24) female soccer players over two Atlantic university Sport seasons (2023 – 24, and 2024 – 25). This research was deemed program evaluation from the Dalhousie Health Sciences Research Ethics Board (REB file#: 2023-6788). Upon arrival to training camp the athletes selected for the Dalhousie University women's soccer program were informed of the study and given the opportunity to consent for each year of the study. Athletes interested in participating provided their informed consent prior to participating in the study. They were all instructed to complete screening documents to ensure they met the eligibility criteria. To be eligible for the study, athletes had to be 17 years of age or older and must have been an active member of the Dalhousie University women's soccer team.

The soccer players were defined into three athlete categories (i.e. starter, finisher, supporter) by the Dalhousie University coaching staff at the start of each week to structure training and preparation for games. Athlete categories also defined which group the athlete's weekly accumulated GNSS and IMU data went to for evaluations of their exercise volume and intensity, and tactical exposures. All participant data were deidentified when evaluating differences between athlete categories.

Prior to the start of data collection StatSports velocity zones were set using Gualtieri et al. 2023 defined thresholds in line with relative athlete max aerobic speeds (19,24,47). Relative velocity thresholds were defined by the final velocity achieved during the Yo-Yo Level 1 intermittent fitness testing scores (50). In accordance with Kavanaugh et al. 2023, max aerobic speed (MAS) was defined by velocity zone 5; where zones 1 and 2 represent low speed running < 60% MAS, zone 3 represents 60% MAS – 80% MAS, zone 4 represents 80% MAS – 100% MAS, zone 5 represents 100% MAS – Sprint Speed entry at 30% anaerobic speed reserve, and zone 6 represents Sprint Speed entry at 30% anaerobic speed reserve – Max Sprint Speed (MSS). Peak velocities were auto populated through StatSports 'Data Tab' and 'Analysis Data for new max speed' function at the conclusion of each game and team training session. Data for total cumulative max aerobic high-speed running distance (HSR – D: m), and rate of high-speed running above max aerobic speed (R-HSR: m/min) will be defined through measures of distance and velocity in relative athlete zones 5 – 6.

3.2 Materials and Instrumentation

3.2.1 Hardware

All team sanctioned training sessions including practices, individual and small unit practices, and games were tracked using the StatSports Apex 10Hz augmented GNSS and integrated IMU sensors (StatSports limited, Newry, Ireland) with accelerometer and gyroscope sampling at 952 Hz, and a magnetometer at 10 Hz. The GNSS units were attached to each athlete between the shoulder blades on their backs using a StatSports GNSS vest worn under training and game jerseys. The GNSS units were turned on 15 minutes prior to the start of each training session or game to ensure acceptable satellite coverage (i.e. minimum of 6 satellites linked to the units) (51).

Figure 2 Displays StatSports manufacturer designed vest and StatSports Apex 10Hz GNSS unit for outfitting athletes.

3.2.3 Software

GNSS and IMU sensor data for each athlete were directly collected by the *APEX Team Series Desktop application* (StatSports limited, Newry, Ireland). The APEX Team Series software was used to break down all game and practice exercise volume (*total cumulative distance covered in a game/practice (m), and high-speed running distance (m)*) and intensity (*average velocity of all movement (m/min), and the rate of high-speed running (m/min)*) metrics for each athlete. The software permits sport practitioners to populate individual athlete profiles for velocity zone preferences and custom MAS relative velocity zones.

StatSports training and in-game exercise volume and intensity athlete data were exported into Excel to be labelled into athlete categories and positions. Excel software was used to de-identify the data, and R Studio version 4.1.2 software was used to conduct analysis on the average exercise training volumes and intensities accumulated during each training period.

All Spiideo collected practice and game tactical video was exported to the Hudl Sportscode software (Agile Sports Technologies, Inc., Lincoln NB, USA) for post practice and game tactical processing (i.e. tag drills based on categorized practice plans). This software was used to quantify the number of tactical exposures athletes achieved on the field and inform drill tagging based on categorized practice plans.

3.3 Procedure and Experimental Design

With the team informed of the project and consent received, players were taught the pre and post practice procedure for handling the units, returning units for charging, and data collection. Athletes were sized for vests, and upon exiting the team locker room coaches ensured the StatSports units were placed into vests according to the manufacturer instructions. Athletes were outfitted with the StatSports units 15-minutes prior to warm-up. GNSS data was cut to the start of the team scheduled warm-up and concluded when athletes were released from the field by the Dalhousie coaching team, at the conclusion of the team scheduled training session, or when the referee ended a game. At the conclusion of practice, the researcher confirmed start and end times for practice on the StatSports time series report, collected StatSport units from the athletes and began syncing unit data to provide reporting to coaches.

During team practices tactical tracking categories were labelled across athletes GNSS *StatSports Team Series desktop software* on the 'time series' function to define drills, as coaches transitioned the team through practice. Drill transition times were tracked so the researcher could go back through the Spiideo on field camera to determine athlete participation and total duration of time spent in drills.

Phase I

Phase I followed the data collection procedure stated under section 3.4 Procedure and Experimental Design. A total of 24 (n = 24) athletes were categorized as starters, finishers, and supporters at the conclusion of the four-weeks of pilot testing to determine exercise volume and intensity per category. Any differences determined between the athlete groups in phase I (year I) were used to determine the magnitude of the exercise volume and intensity and tactical exposure intervention implemented by the coaching staff for phase II (year 2).

Phase II

Similar to phase I, phase II followed the data collection procedure detailed above with a total of 24 (n = 24) athletes. In phase II the Dalhousie coaching staff implemented a training intervention with the Dalhousie women's soccer team to minimize exercise volume and intensity discrepancies between starters, finishers and supporting athletes. Athlete categories were communicated to the researcher at the beginning of the training week to help the researcher and coaching staff plan the intervention and training opportunities for lower minute athletes. Bi-weekly exercise volume and intensity analyses were conducted on the differences between athlete categories. The Dalhousie coaching staff were provided with post practice and game measures of volume and intensity, as well as differences between athlete categories and position groupings to build on weekly communication and planning.

The phase II intervention built on cumulative bi-weekly exercise volume and intensity analysis and targeted transition days between games in match day + 1 /match day -7 and match day – 1. The intervention aimed to increase exercise volume and intensity in low-minute athletes while maintaining or reducing large bouts of exercise volume and intensity in starters. As the season progressed match day -1 volumes were greatly reduced in starters and finishers to ensure a higher level of readiness to play in games. During match days, supporters completed top-up runs targeted at increasing exercise volume and intensity through on ball play and the use of MAS runs to ensure they were reaching individualized thresholds. During weeks with back-to-back games, the first match day top-up training session targeted small-sided games and tactical components with reduced TD (m) and HSR-D (m), followed by a second match day training session targeted at increasing supporters' exposure to intensive training mimicking match day +2/ match day – 5 format outlined by Doyle et al., (2022).

3.4 Data Analysis

The exercise volume and intensity data does not maintain independence of participants because athletes could move between starter, finisher, and supporter categories throughout the season. This violates a core assumption of the MANOVA; therefore, a linear mixed-effects model was used to determine category differences in phase I and phase II, year 1 and year 2, respectively.

3.4.1 Phase I: Exercise Volume and Intensity Analysis

A linear mixed effect (LME) model (lme4 v1. 1-29 in R version 4.1.2) was constructed to evaluate fixed effects between athlete groups and random effects for athletes' groups, to determine potential differences for dependent variables – including measures of volume (total cumulative weekly distance (m), cumulative high-speed running distance (HSR-D: m)) and measures of intensity (total weekly velocity (m/min), and rate of high-speed running above max aerobic speed (R-HSR: m/min)) between starters, finishers, and supporters. Prior to running the model, a Shapiro-wilk test was used to evaluate normality. To assess residual normality for each dependent variable, q-q plots were generated using stacked standardized residuals. Scatterplots of the stacked unstandardized and standardized residuals were used to assess the error of variance associated with the residuals. For the inclusion of fixed effects variables, a Chi-squared test (models with and without variables comparison) was implemented and both Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) was used to inform the best model fit.

To further investigate the differences between athlete categories, Bonferroni pairwise comparisons were completed on all dependent variables. Marginal R^2 was also reported to express the proportion of variance in the dependent variables that can be explained by the fixed variables (i.e. competition category). R^2 was classified as very weak ($R^2 < 0.02$), weak ($0.02 = R^2 < 0.13$), moderate ($0.13 <= R^2 < 0.26$), and substantial ($R^2 >= 0.26$) as suggested by Cohen (1988).

3.4.2 Phase II: Exercise Volume and Intensity Analysis

Phase II analysis included both Phase I and II data sets to increase model sample size and conduct a single combined analysis. The linear mixed effects models (lme4 and lmerTest v1. 1-29 in R version 4.1.2) were used to evaluate the effects of athlete categories and training periods on measures of exercise volume and intensity. This would determine if differences between athlete categories could be minimized between years (phase I and phase II) and throughout a full season (phase II). Time between years (phase I and phase II) was coded as a factor comparing phase I against each phase II training period and the cumulative phase II data set. The addition of position as a fixed effect was explored; however, it produced no effect and increased AIC and BIC values compared to the LME4 model with position removed and led to no significant differences between groups. Therefore, position was removed from the phase II model.

Prior to running the model, a Shapiro-wilk test was used to evaluate normality. To assess residual normality for each dependent variable, q-q plots were generated using stacked standardized residuals. Scatterplots of the stacked unstandardized and standardized residuals were used to assess the error of variance associated with the residuals. For the inclusion of fixed effects variables, a Chi-squared test (models with and without variables were comparison) was implemented and AIC and BIC were used to inform best model fit.

In the case of significant outcomes, the differences between athlete categories over time (phase II) were compared with Bonferroni pairwise comparisons for each training period (1-5) and all dependent variables. Marginal R^2 was also reported to express the proportion of variance in the dependent variables that was explained by the fixed variables (i.e. competition category).

3.4.3 Phase II: Tactical Analysis

A linear mixed effects model (lme4 and lmerTest v1. 1-29 in R version 4.1.2) was used to evaluate fixed effects between athlete categories and drill classification for measures of athlete tactical exposure throughout phase II (year II). Athlete Categories were modelled as fixed effects in the analysis of tactical drill classification with total time modelled as a random effect. The addition of position as a fixed effect was explored; however, it produced no effect and increased AIC and BIC values compared to the LME4 model with position removed and led to no significant differences between groups. Therefore, position was removed from the phase II tactical analysis.

Prior to running the model, a Shapiro-wilk test was used to evaluate normality. To assess residual normality for each dependent variable, q-q plots were generated using stacked standardized residuals. Scatterplots of the stacked unstandardized and standardized residuals were used to assess the error of variance associated with the residuals. For the inclusion of fixed effects variables, a Chi-squared test (models with and without variables were comparison) was implemented and AIC and BIC were used to inform best model fit.

Bonferroni pairwise comparisons were completed on the four drill classifications for all dependent variables. Marginal R^2 was also reported to express the proportion of variance in the dependent variables that can be explained by the fixed variables (i.e. competition category).

Chapter 4: Results

4.1 Phase I Results

Significant outcomes were determined in three of the measures of exercise volume and intensity.

Exercise Volume

There were significant total distance (m) differences identified between supporters (intercept) and starters (MD = 18,303.08, SE = 5,655.45, p = 0.001), and significant HSR-D (m) differences between supporters and starters (MD = 1,585.49, SE = 486.91, p = 0.003) in the first year of data collection (Figure 3).

Exercise Intensity

There were no significant mean differences identified between athlete categories for measures of total weekly velocity (m/min). However, significant R-HSR (m/min) differences were identified between supporters and starters (MD = 1.74, SE = 0.45, p < 0.001) and finishers versus starters (MD = 1.17, SE = 0.43, p = 0.007) (Figure 3).

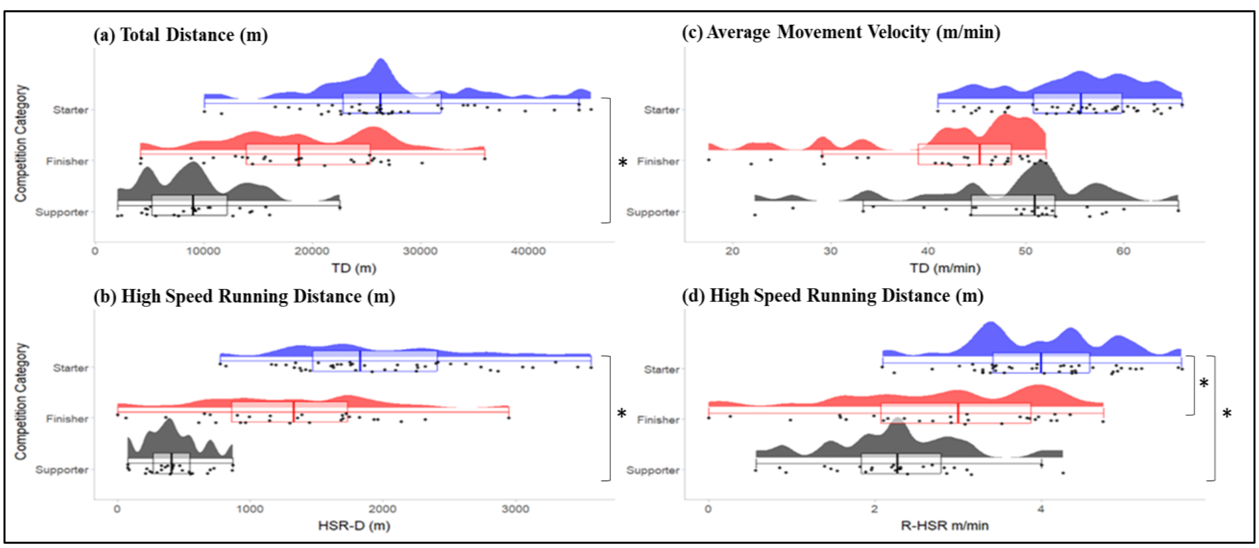


Figure 3 Displays Phase I (year I): Measures of Exercise Volume and Intensity results for the comparison of starters, finishers, and supporters through the pilot training period for four measures of

mean weekly exercise volume and intensity. Graph (a) displays mean weekly total cumulative distance (m), (b) displays mean weekly cumulative high-speed running distance (HSR-D m), (c) displays mean total weekly cumulative velocity (m/min), and (d) displays mean weekly rate of high-speed running above max aerobic speed (R-HSR: m/min). Significance is denoted by the asterisk (*), brackets indicate significance between athlete categories

4.2 Phase II Results

4.2.1 Exercise Volume (Weekly total cumulative distance)

Phase I (year 1) versus Phase II (year 2)

There were significant increases in total distance (m) for *supporters* (MD = 8,774.09, SE = 1,787.24, $p < 0.001$) and *finishers* (MD = 3,512.73, SE = 1,768.41, $p = 0.047$) from phase I to phase II. The increased total distance for *supporters* and *finishers* resulted in a significant decrease in total distance between *supporters* and *finishers* (MD = -5,261.36, SE = 2,514.27, $p = 0.037$), and *supporters* and *starters* (MD = -7,709.09, SE = 2,289.88, $p = 0.001$) in phase II compared to phase I (Figure 4). Overall, there were no significant differences in weekly total distance between *finishers* and *supporters* (MD = 4,505, SE = 6,700, $p = 1.000$), *finishers* and *starters* (MD = -6,089.0, SE = 6,680, $p = 1.000$), and *supporters* and *starters* (MD = -10,594, SE = 6,680, $p = 0.3378$) in phase II.

Training Period Comparisons (Between Athlete Categories)

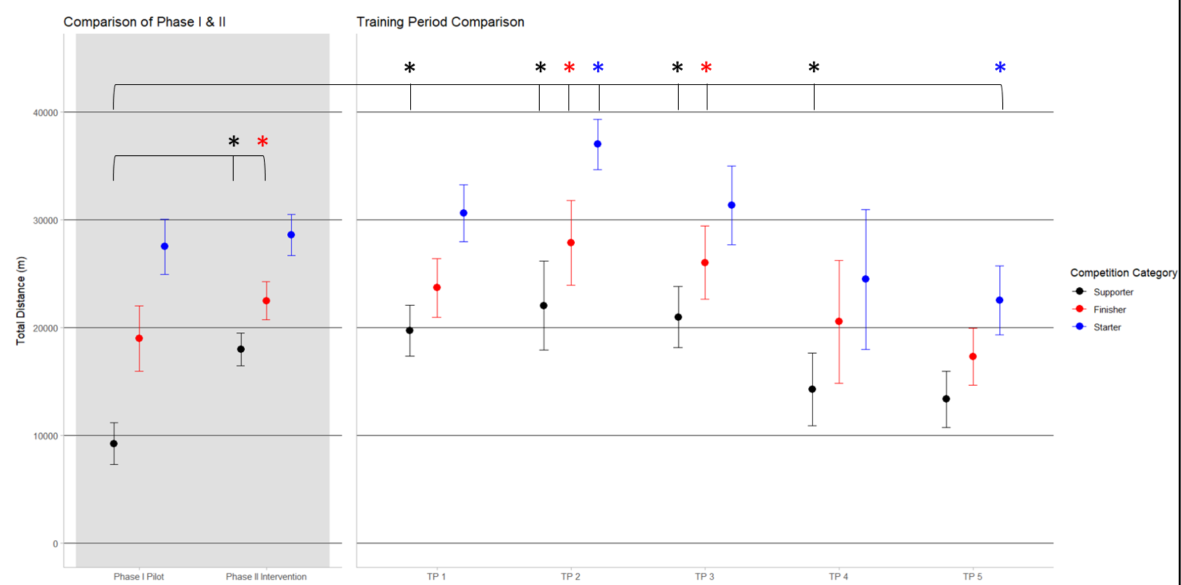
Significant reductions between supporters and starters in total distance (m) were observed in phase II training periods (TP) 1 and 3 - 5 compared to phase I: (TP1: MD = -7,412.08, SE = 3,122.85, $p = 0.018$), (TP3: MD = -7,934.49, SE = 3,164.13, $p = 0.013$), (TP4: MD = -8,083.88, SE = 3,211.10, $p = 0.012$), and (TP5: MD = -9,128.81, SE = 2,842.34, $p = 0.001$; Figure 4). Predicted percent variability of variance for estimated marginal $R^2 = 0.385$ for the total distance (m) model.

Training Period Comparisons (Within Athlete Categories)

There were significant increases in *supporter* mean weekly total distance for training periods (TP) 1 – 4 compared to phase I: (TP1: MD = 10,503.56, SE = 2,393.64, p < 0.001), (TP2: MD = 12,830.01, SE = 2,302.62, p < 0.001), (TP3: MD = 11,762.86, SE = 2,447.25, p < 0.001), and (TP4: MD = 5,038.61, SE = 2,507.69, p = 0.045; Figure 4 - Black). The within training period mixed-effects model outcomes are in Appendix B (Table 1).

There were significant increases in *finisher* mean weekly TD (m) for training period 2 (MD = 8,898.57, SE = 2,626.98, p = 0.001) and training period 3 (MD = 7,048.74, SE = 2,477.66, p = 0.005: Figure 4 – Red).

A significant increase in *starter* weekly total distance (m) occurred in training period 3 (MD = 9,476.13, SE = 2,005.66, p < 0.001) and training period 5 (MD = -4,995.49, SE = 1,764.74, p = 0.005) compared to phase I (Figure 4 - Blue).



	Phase I Pilot	Phase II Intervention	TP 1	TP 2	TP 3	TP 4	TP 5
Finisher (MD)	9,766.65 m	4,505.30 m*	3,964.50 m	5835.20 m	5052.50 m	6,293.40 m	3,957.10 m
Starter (MD)	18,303.08 m	10,594.00 m***	10,891.00 m *	14,949.20 m	10,368.50 m *	10,219.20 m *	9,174.30 m ***

Figure 4 Displays measures of mean weekly total distance (m). The grey area (left) depicts the weekly averages of total distance for each athlete category during phases I and II. The white area

(right) depicts the phase II weekly total distances for each athlete category in 2-week training periods. Significance is denoted by the asterisk (*), which are colour coded to athlete category.

4.2.2 Exercise Volume (Weekly high-speed running distance)

Phase I (year 1) versus Phase II (year 2)

There were significant increases in mean weekly high-speed running distance (HSR – D: m) for supporters between phase I and phase II (MD = 1,243.44, SE = 217.99, $p < 0.001$), with no significant differences for finishers or starters (Figure 5). There were significant reductions in the mean differences between *supporters* and *finishers* (MD = -1,125.65, SE = 279.29, $p < 0.001$), and *supporters* and *starters* (MD = -1109.01, SE = 306.66, $p < 0.001$) in phase II compared to phase I. Overall, there were no significant differences in weekly total distance between *finishers* and *supporters* (MD = -231.20, SE = 457, p = 1.00), *finishers* and *starters* (MD = -691.0, SE = 453, p = 0.3812), and *supporters* and *starters* (MD = -459.8, SE = 453, p = 0.9243) in phase II.

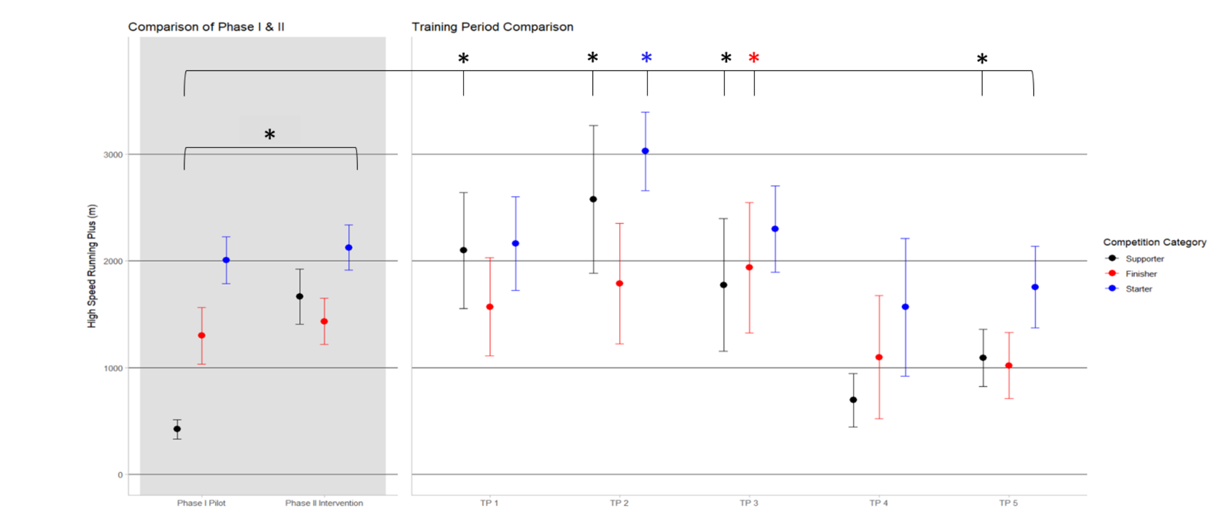
Training Period Comparisons (Between Athlete Categories)

Significant mean difference reductions between *supporters* and *starters* were observed during training periods 1 – 3 and 5 compared to phase I: (TP1: MD = -1517.94, SE = 368.20, $p < 0.001$), (TP2: MD = -1,1133.19, SE = 360.00, p = 0.002), (TP3: MD = -1,063.96, SE = 373.00, p = 0.005), and (TP5: MD = -922.51, SE = 335.10, p = 0.006: Figure 5). Significant mean difference reductions were also observed between *supporters* and *finishers* during training periods 1, 2 and 5 compared to phase I: (TP1: MD = -1,405.01, SE = 406.20, p = 0.001), (TP2: MD = -1,666.07, SE = 411.80, $p < 0.001$), and (TP5: MD = -951.08, SE = 371.70, p = 0.011: Figure 5). Predicted percent variability of variance for estimated marginal $R^2 = 0.330$ for the HSR – D (m) model.

Training Period Comparisons (Within Athlete Categories)

There were significant increases in *supporter* mean weekly HSR-D (m) for training periods (TP) 1 – 3, and 5 compared to phase I (TP1: MD = 1,675.13, SE = 282.19, p < 0.001), (TP2: MD = 2,153.76, SE = 271.47, p < 0.001), (TP3: MD = 1,353.11, SE = 288.51, p < 0.001), and (TP5: MD = 670.41, SE = 262.68, p = 0.011: Figure 5 - Black). The linear mixed-effects model outcomes are represented in table 3 (Appendix B).

Phase II did not result in a significant difference in mean weekly HSR-D (m) for *finishers* compared to phase I. However, during training period 3 there was a significant increase in HSR-D compared to phase I (MD = 636.63, SE = 292.10, p = 0.03: Figure 5 - Red). Similarly, there was not a significant difference in mean weekly HSR-D for *starters* in phase II compared to phase I (numbers). However, during training period 2 (MD = 1,020.58, SE = 236.45, p < 0.001) there were significant increases in HSR-D compared to phase I (Figure 5 - Blue).



Finisher (MD)	877.83 m	- 230.90 m	- 527.10 m**	- 788.30 m***	161.4 m	401.80 m	- 73.20 m*
Starter (MD)	1,585.49 m	489.90 m	67.90 m***	452.30 m**	521.50 m**	870.30 m	663.00 m*

Figure 5 Displays measures of mean weekly High Speed Running Distance HSR-D (m). The grey area (left) depicts the weekly average total HSR-D for each athlete category during phases I and II. The white area (right) depicts the phase II weekly HSR-D for each athlete category in 2-week training periods. Significance is denoted by the asterisk (*), which are colour coded to athlete category.

4.2.3 Exercise Intensity (Weekly velocity)

Phase I (year 1) versus Phase II (year 2)

There were no significant differences observed between athlete categories in phase I; however, there were significant increases in weekly velocity (m/min) for *finishers* (MD = 7.24, SE = 2.10, $p = 0.001$), and *starters* (MD = 6.54, SE = 1.70, $p < 0.001$: Figure 6) in phase II. There were also significant mean difference increases between *supporters* versus *finishers* (MD = 6.74, SE = 2.98, $p = 0.024$), and *supporters* versus *starters* (MD = 6.04, SE = 2.71, $p = 0.027$; Figure 6) in phase II compared to phase I.

Training Period Comparisons (Between Athlete Categories)

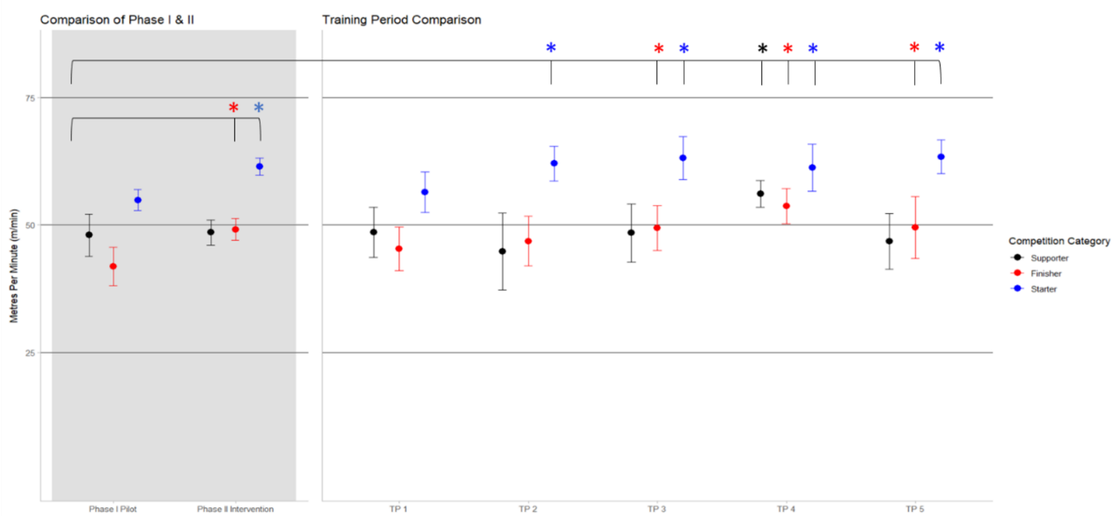
Significant mean difference increases were identified between *supporters* and *starters* during training periods 2,3 and 5 compared to phase I: (TP2: MD = 10.40, SE = 3.79, $p = 0.006$), (TP3: MD = 7.82, SE = 3.93, $p = 0.047$), and (TP5: MD = 9.72, SE = 3.53, $p = 0.006$: Figure 6). Significant mean difference increases were also observed in *supporters* and *finishers* were observed during training period 5 compared to phase I: (TP5: MD = 8.90, SE = 3.91, $p = 0.024$: Figure 6). Predicted percent variability of variance for estimated marginal $R^2 = 0.223$ for weekly velocity (m/min) model.

Training Period Comparisons (Within Athlete Categories)

Phase II did not result in a significant difference in *supporter* mean weekly velocity (m/min) compared to phase I. However, during training period 4 there were significant increases in mean weekly velocity (m/min) compared to phase I (MD = 8.07, SE = 3.12, $p = 0.01$: Figure 6 – Black).

There were significant increases in *finisher* mean weekly velocity (m/min) for training periods (TP) 3 – 5 compared to phase I supporters: (TP3: MD = 7.52, SE = 3.07, p = 0.015), (TP4: MD = 11.80, SE = 3.00, p < 0.001), (TP5: MD = 7.64, SE = 2.77, p = 0.006: figure 6 – Red).

There were significant increases in *starter* mean weekly (m/min) for training periods (TP) 2 – 5 compared to phase I supporters: (TP2: MD = 7.16, SE = 2.49, p = 0.004), (TP3: MD = 8.22, SE = 2.49, p = 0.001), (TP4: MD = 6.38, SE = 2.49, p = 0.011), (TP5: MD = 8.45, SE = 2.19, p < 0.001: figure 6 – Blue).



	Phase I Pilot	Phase II Intervention	TP 1	TP 2	TP 3	TP 4	TP 5
Finisher (MD)	-6.15 m/min	0.60 m/min**	-3.20 m/min	2.00 m/min	1.00 m/min	-2.40 m/min	2.70 m/min*
Starter (MD)	6.88 m/min	12.9 m/min*	7.90 m/min	17.30 m/min**	14.70 m/min*	5.20 m/min	16.50 m/min**

Figure 6 Displays measures of mean weekly velocity (m/min). The grey area (left) depicts the weekly average total m/min for each athlete category during phases I and II. The white area (right) depicts the phase II weekly m/min for each athlete category in 2-week training periods. Significance is denoted by the asterisk (*), which are colour coded to athlete category.

4.2.4 Exercise Intensity (Weekly rate of high-speed running (R-HSR: m/min))

Phase I (year I) versus Phase II (year 2)

There were significant increases in weekly rates of high-speed running (R-HSR: m/min) for supporters (MD = 1.96, SE = 0.39, p < 0.001) from phase I to phase II. Increases in R-HSR (m/min) for *supporters* resulted in a significant decrease in R-HSR (m/min) between *supporters* and *finishers* (MD = -1.82, SE = 0.55, p = 0.001), and *supporters* and *starters* (MD = -1.50, SE = 0.50, p = 0.003). Overall, there were significant differences in weekly R-HSR (m/min) between all athlete categories *supporters* and *finishers* (MD = 1.25, SE = 0.35, p = 0.0011), and *finishers* and *starters* (MD = -1.49, SE = 0.334, p < 0.001).

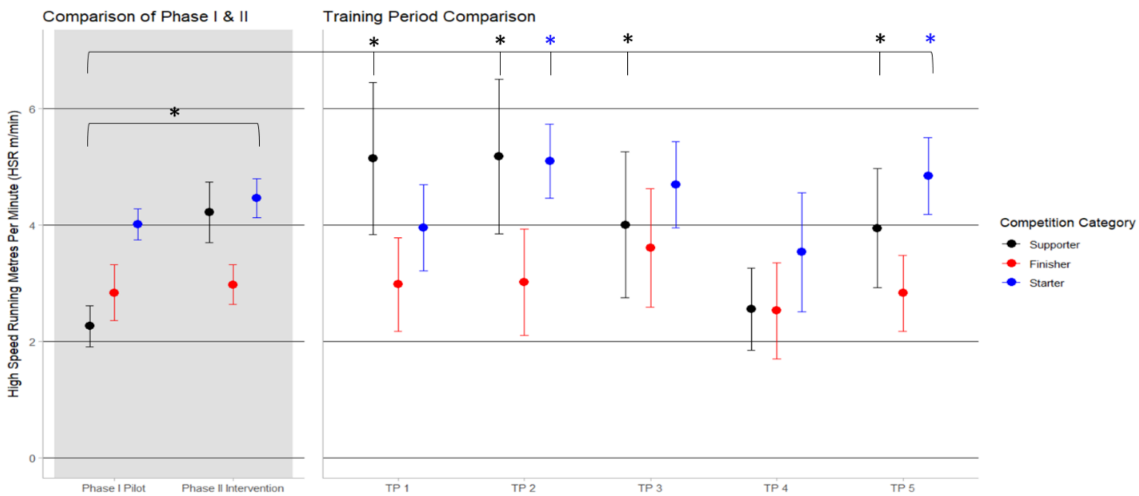
Training Period Comparison (Between Athlete Categories)

Significant reductions between *supporters* and *starters* in R-HSR (m/min) were observed in phase II training periods 1 and 2 compared to phase I: (TP1: MD = -2.94, SE = 0.68, p < 0.001), and (TP2: MD = -1.83, SE = 0.67, p = 0.007: Figure 7). Significant mean difference reductions were also observed in *supporters* and *finishers* during training periods 1, 2, and 5 compared to phase I (TP1: MD = -2.74, SE = 0.75, p < 0.001), (TP2: MD = -2.73, SE = 0.76, p < 0.001), and (TP3: MD = -1.69, SE = 0.69, p = 0.015: Figure 7). Predicted percent variability of variance for estimated marginal R^2 = 0.251 for the R-HSR (m/min) model.

Training Period Comparisons (Within Athlete Categories)

There were significant increases in *supporter* mean weekly R-HSR (m/min) for training periods (TP) 1 – 3, and 5 compared to phase I supporter: (TP1: MD = 2.88, SE = 0.52, p < 0.001), (TP2: MD = 2.91, SE = 0.50, p < 0.001), (TP3: MD = 1.74, SE = 0.54, p = 0.001), and (TP5: MD = 1.68, SE = 0.48, p = 0.001: Figure 7 - Black). The linear mixed-effects model outcomes are represented in table 5 (Appendix B).

There were significant increases in *starter* mean weekly R-HSR (m/min) in training period 2 (MD = 1.09, SE = 0.44, p = 0.014), and training period 5 (MD = 0.84, SE = 0.39, p = 0.031) compared to phase I (Figure 7 – Blue).



	Phase I Pilot	Phase II Intervention	TP 1	TP 2	TP 3	TP 4	TP 5
Finisher (MD)	0.57 m/min	-1.20 m/min**	-2.10 m/min**	-2.20 m/min**	-0.40 m/min	0.00 m/min	-1.10 m/min*
Starter (MD)	1.17 m/min	0.30 m/min**	-1.10 m/min***	-0.10 m/min**	0.70 m/min	1.00 m/min	0.90 m/min

Figure 7 Displays measures of mean weekly rate of high-speed running R-HSR (m/min). The grey area (left) depicts the weekly R-HSR m/min for each athlete category during phases I and II. The white area (right) depicts the phase II weekly R-HSR m/min for each athlete category in 2-week training periods. Significance is denoted by the asterisk (*), which are colour coded to athlete category.

4.2.5 Tactical Exposure Differences (Total time spent in drill segments)

There were no significant differences observed between athlete categories for all drill classifications. In the evaluation of total time spent in live game play, *starters* had the greatest total time; however, no significant differences were identified between athlete categories in *supporters* versus *starters* (MD = 1,028.98, CI = -168.52 - 2,226.48, p = 0.089) and *supporters* versus *finishers* (MD = 612.0, CI = -585.47 - 1,809.52, p = 0.305).

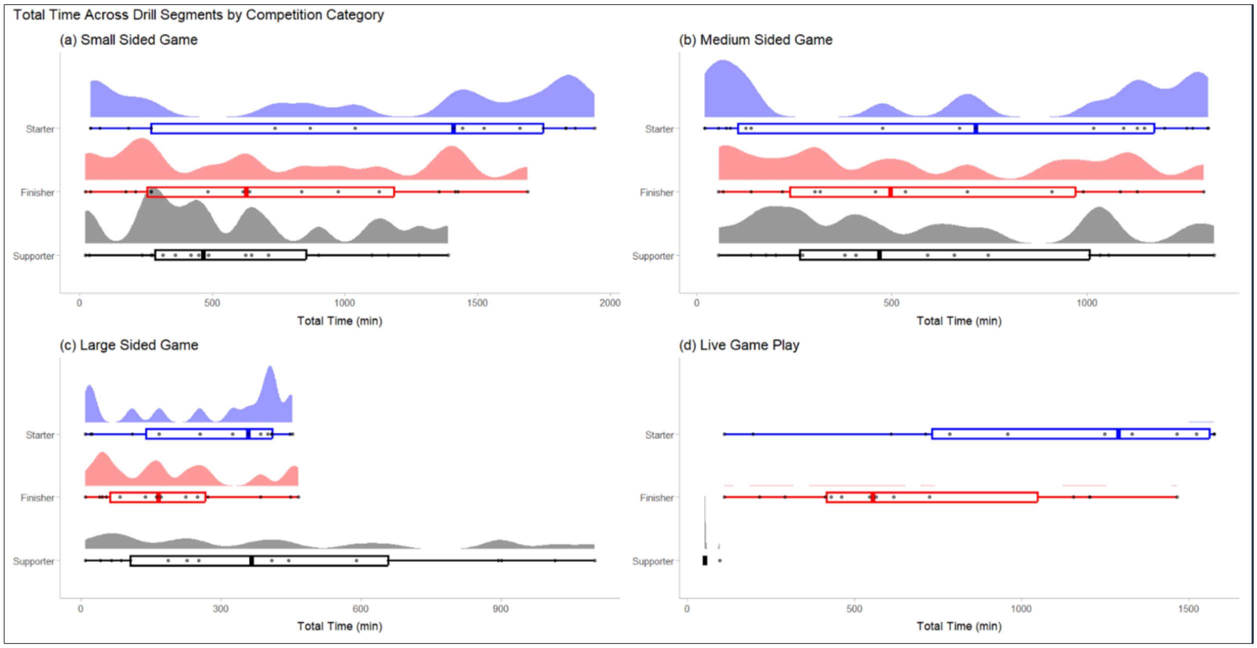


Figure 8 Displays tactical exposure differences (total time) for four drill classification boxplots: a) Small Sided Games (b) Medium Sided Games, (c) Large Sided Games, and (d) Live Game Play. The athlete categories are starter (blue), finisher (red), and supporter (black) and they are all plotted against total time (minutes) spent in each tactical drill.

Chapter 5: Discussion

This research project completed its primary purpose of implementing a GNSS and integrative IMU athlete tracking system to determine exercise volume and intensity differences between high-minute (starters) and low-minute (finishers and supporters) women soccer athletes. In phase I significant differences were identified between starters and supporters for measures of TD (m), HSR-D (m), R-HSR (m/min). However, in phase II an integrated coaching intervention decreased these differences between athlete categories.

Phase I versus phase II results showed significant increases in supporter and finisher TD (m) and HSR – D (m) exercise volume metrics. Measures of TD (m) significantly increased in phase II through training period (TP) 1 – 4 compared to phase I in supporters, and through TP 2 – 3 in finishers, and TP 3 for starters. For measures of total cumulative HSR-D (m), phase II had significant increases in supporter volumes through TP 1 – 3 and 5 with significant reductions between starters and supporters, and starters and finishers. HSR-D (m) also significantly increased in finishers during TP 3, and starters during TP 2; however, there were no significant overall changes observed between phase I and phase II for finishers and starters.

There were also significant differences observed in the exercise intensity metrics. Measures of weekly velocity (m/min) significantly increased between phase I versus phase II in starters and finishers, with no increases in supporters. For measures of R-HSR (m/min) in phase II, there were significant mean difference reductions observed between starters and supporters, and starters and finishers.

This research project also completed its secondary purpose of tactical drills analysis, where no statistical differences were observed between athlete categories in tactical drill exposure time.

5.1.1 Phase I (year I) Exercise Volume

The significant differences between athlete categories in phase I resulted in inadequate preparation for lower minute athletes. Gabbett et al. (2016) identified overuse injuries occur through both ‘overload’ and ‘underloading’ athletes through measures of TD (m) and HSR-D (m) (33). Increased injury risk is associated with large spikes in acute measures of exercise volume and intensity (33). Our phase I results identified that low minute athletes were ‘predisposed’ to exercise volume and intensity spikes when stepping into high-minute athlete roles due to ‘low chronic workloads’ or significant TD (m) and HSR-D (m) shortcomings compared to starters.

Undertraining also has the potential to increase injury risk and leave athletes underprepared; however, there is potential for high-minute athletes to shoulder significant exercise volume and intensity spikes from training and games (33). Our phase I results indicated large spikes in weekly TD (m) for starters that are far greater than the recommended ideal 3.0 times game volumes, leaving starters at risk for injury (22,26). With university sport game schedules occurring on weekends in the format of back-to-back games, coaching teams should expect and plan to adjust for high-minute starters across U- Sports programs to experience spikes in TD (m) and HSR-D (m), while low-minute athletes being susceptible to reduced levels of volume and intensity exposure.

5.1.2 Phase I (year I) Exercise Intensity

In phase I the supporter athlete group had the greatest discrepancy for measures of average velocity (m/min) and R-HSR (m/min) compared to starters and finishers. Measures of weekly average velocity (m/min) were recorded at or below 40 m/min in supporters and finishers compared to 55 m/min for starter athletes, suggesting that low minute athletes are spending significant periods of training in stoppage or outside of competitive drills (23).

Measures of R-HSR (m/min) help coaches examine the rate of exercise exposure to high-speed transition play and represent greater play intensity. Significant exercise intensity differences between athlete categories are potentially due to reduced R-HSR training opportunities for supporter and finisher athletes, and reduced game substitutions later in the season. Rate of high-speed running (m/min) peak during periods of game play that involve 20 - 25 meters of relative R-HSR (m/min) above each athletes MAS. These values which represent 2.0 - 2.5 times average game play values experienced by starters. These peak periods of game play are not experienced by low minute athlete categories (finishers and supporters). This demonstrated a significant gap in athlete development for low minute athlete categories, and a potential physical development gap between athlete categories through the late season training environment.

5.2.1 Phase II (year II) Supporter Volume and Intensity

Researching the supporter role and identifying differences from starters and low-minute athletes is unique to university sport; there are a significant number of athletes recruited into supporter roles who progress towards starter or finisher roles in following years. The phase II coaching intervention was primarily implemented to address large gaps between high-minute and low-minute athletes in measures of exercise volume and intensity. The intervention successfully reduced gaps in TD (m), HSR-D (m), and R-HSR (m/min) between starters and supporters, on top of seeing large TD (m) volume increases in starters. However, average weekly velocity of all play (m/min) was consequentially reduced in supporters because of long rest periods. In phase I average weekly velocity (m/min) was not significantly different between athlete categories, and therefore the phase II intervention focused on targeted increases in TD (m) and HSR-D (m). The time spent increasing exercise volume through skill-based top-ups and max aerobic speed (MAS) runs resulted in TD (m) and HSR-D (m) improvements. However, these targeted increases resulted in greater low intensity running volumes causing the average weekly movement velocities (m/min) to decrease.

Improvements in HSR-D (m) and R-HSR (m/min) likely occurred because of targeted large sided game 'top-ups' that used MAS runs with long rest intervals that permitted supporters to reach MAS thresholds. These improvements in high-intensity drill exposures indicated athletes were ready to perform in high-intensity transitions, simulated live-game play in practice. This identifies the importance of consistent and targeted high-speed running above MAS over the course of the season. This intervention prepared the supporter, low minute, athlete to step into a finishing role, and suggests that supporters should be better equipped to compete in high-intensity full field drills and contribute to pushing starters towards a higher rate of play. Most research focusing on high-minute versus low-minute athletes, to date, has not addressed supporters in their analysis.

5.2.2 Phase II (year II) Finisher Volume and Intensity

In phase II total cumulative improvements in measures of TD (m) and average weekly velocity (m/min) were increased in finishers relative to phase I. These outcomes were similar to Bortnik et al. (2023), where prior to intervention, finishers experienced reduced TD (m) volumes (28,30). Measures of intensity, R-HSR (m/min), also showed similar significant gaps between starters and low-minute athletes (28). Bortnik et al. (2023) theorized that finishers may not be exposed to intense periods of match play when substituted into the second half of games due to substitutions occurring when leads are safe or when the game is out of reach. Therefore, with fewer in-game high intensity minutes as well as fewer targeted maximum intensity training opportunities, finishers are not properly prepared to match a starter's measure of high-speed running. For measures of HSR-D (m) and R-HSR (m/min) the finisher group saw phase I trends continue into phase II; despite targeted increases in measures of TD (m) and total weekly velocity (m/min), measures of HSR-D (m) and R-HSR (m/min) did not significantly increase.

The phase II period analysis (every two-weeks) identified significant improvements across all metrics for finishers; however, improvements were not consistent across all training periods. This is the reality of how variable and challenging the finisher role is for athletes, and the coaching team when projecting measures of volume and intensity. These variable outcomes suggest the need to better periodize high-speed running exposures for finisher athletes to reduce the competitive gap between finisher and starter roles. Small intervention adjustments were made within phase II to weekly training on match day + 1 (i.e. day following a match) and/or match day – 5 (i.e. 5 days prior to a match) which led to exercise volume reductions between starter and finisher athletes. During mid-season phases, where high-minute athletes experienced high-in game volumes, finishers became the focal point of practices resulting in TD (m) volumes greater than 23,500m for TP 1 – 3. Through these training adjustments TD (m) differences between starters and finishers decreased from 8,536.43m (phase I) to 6,099.90m (Phase II), but it was not significant.

5.2.3 Phase II (year II) Starter Volume and Intensity

Cumulative results between phase I and Phase II identified significant increases in measures of exercise intensity for average weekly velocity of all play (m/min), with some significant training period increases in R-HSR (m/min) and TD (m). Cumulative TD (m) and

HSR-D (m) volumes were greater in starters through early training periods. This could represent competitive training in practices during early periods of the season, with a shift in later training periods toward targeted tactical adjustments to reduce volume and training intensity through set pieces or isolated drills, medium sided games, and walk throughs.

Previous research evaluating measures of TD (m) and HSR-D (m) in starters versus low-minute athletes identified that the NCAA game schedule produced significantly greater exercise volumes in starters compared to low-minute athletes (23). Significant differences in TD (m) and HSR-D (m) come from game play and were not due to differences in practice (23). In the NCAA and Canadian University sport, there are several factors that contribute to TD (m) and HSR-D (m) differences, including athletes' competition schedule format with back-to-back games, and rule differences which permit coaches to make unlimited substitutions within games and re-enter their starters at the conclusion of close games.

Total weekly distance for starters in professional women's soccer are 22 – 28 km (27), with reported training/practice total distance volumes of 16 – 22 km; with the goal to have training distance be 2.0 - 2.5 times their competition distance (8 km to 11 km) (10,25–27). These distances are regarded as heuristics for endurance sport athletes and align with research conducted in professional women's soccer; however, total weekly distances were greater in our population versus researched totals in professional women's soccer. In phase I starters averaged 27,523 m and 28,588 m in phase II, with some training period team weekly averages recorded as high as 37,000 m. Although there were significant reductions in measures of TD (m) between starters and supporters, and insignificant differences between starters and finishers there are still relatively large TD differences between athlete categories. Through phase II, weekly differences between starters and finishers were often minimized to the equivalent of one high-intensity practice or 45 minutes of game volume. In the supporter athlete grouping, the mean difference with starters in phase II was equivalent to two high-intensity training sessions or the difference of one 90-minute game.

Previous research evaluating practice exercise volumes, HSR-D (m) and TD (m), had findings that were consistent with our population's practice volumes (11). Doyle et al. (2022) defined low volume training sessions as TD (m) = 3,339.50m, occurring regularly on match day + 1 /match day -7, with the most intensive training occurring on match day -5 (TD (m) = 5,933.5m and HSR – D (m) = 575m) and match day -2 (TD (m) = 5,151.5m and HSR – D (m) = 250m). Although this was not this studies research focus, the alignment in daily session totals between Doyle et al. (2022) and this project identify the next steps in mitigating within team differences for measures of exercise volume. For example, an intervention may not require completely minimizing total cumulative training volume differences between athlete categories because starter volumes are highly variable.

Starters had exercise intensity weekly average velocity (m/min) and R-HSR (m/min), increases as the season progressed. Reductions in measures of TD (m) in training may have contributed to an increased athletic ability to reach greater in-game intensities towards the end of the season. Increases in exercise intensity with reduced TD (m) as the season progressed resulted in the low-minute athletes drop in exercise volumes that were just outside of ideal ranges (28); however, the adjustments assisted in shifting high-minute athletes toward increased measures of exercise intensity while sustaining highly competitive weekly average velocity (m/min) and R-HSR (m/min) late in the season. Bortnik et al. (2023) presented similar findings on high-minute athletes, lower outputs are often detected in starters during periods where self-pacing strategies (conscious or subconsciously) are often used to minimize physical effort and preserve energy (27). These findings emphasize the need for further investigations into the importance of practice quality and volume management during weeks with back-to-back games or early season periods where there are large spikes in exercise volume.

5.3 Phase II (year II) Tactical Exposures

Tagging drill segments provided the coaching team with context to the typical exercise volume and intensity of each drill set. Increased exposure time to large area games for supporters was implemented in phase II to reduce expected differences established through starter game play; however, large area games time increases for supporters and live game play time increases for starters did not produce significantly different results between athlete categories. Non-significance may have occurred because of our model design, where athletes were permitted to move between groups which violates group independence. In tagging drill segments, athletes who may have only registered a few games in finishing and starting roles may have affected confidence intervals and significance levels between athlete categories. Therefore, despite having large mean athlete category differences in live game play and large sided games there were no significant outcomes because of the large confidence intervals.

5.4 Strengths & Limitations

Study Design Strengths

The portability of the StatSports GNSS made tracking integration in year I and II highly efficient and permitted the direct measures of exercise volume and intensity. Data processing on APEX Team Series software permitted custom MAS velocity zones to accurately quantify intensity, compared to absolute HSR ranges that may have mischaracterized some athlete's exercise intensity.

The use of two-week training periods permitted a safe adjustment period for the coaching team and support staff to evaluate progressive changes in training between athlete categories. Top-up exposures through phase II aimed at reducing HSR-D (m) and TD (m) mean differences between groups without over-reacting to acute differences between high-minute and low-minute athletes during single weeks. The format of using a two-week segment also allowed the coaching team to distribute multiple lower volume, higher intensity top-up sessions throughout the duration of the week and support athletes in and out of the lineup.

The coaching team and performance staff were informed on training session upper limits outlined by Bortnik et al. (2023), Doyle et al. (2022), and Canada soccer guidelines. Top-ups were implemented for supporters with low in-week training volumes and on game days, while the first day post-match (MD+1) was utilized to implement targeted increases in volume and intensity for all low-minute athletes. This method allowed the coaching team to address substantial exercise volume and intensity gaps between athlete categories without overtraining any group.

Study Design Limitations

Our research was designed to track and test the Dalhousie women's soccer team and therefore our findings may only be relevant to the Canadian university sport population. This research was conducted and paused in accordance with team schedules, holidays, and student exams. Athletes who were injured or not cleared for gameplay by the Dalhousie medical team were categorized as supporters. Training limitations set by medical professionals were fully respected, and provided constraints on athlete's daily top-up runs which limited an athlete's ability to build exercise volume and intensity; therefore, injured athlete data may have decreased the supporter exercise volume and intensity metrics. Also, athlete samples in phases I and phase

II were coded as the same because the athlete population was highly similar; however, the populations were not identical between phase I and II because of annual turnover due to graduating and incoming athletes. As a result, the LME coding did not account for repeated measures within individuals across phases. During training period 4 we saw significant reductions in measures of volume TD (m) and HSR (m) that occurred because of holidays and reduced opportunities to implement match day +1 top-ups. Due to significant reductions in volume there were planned intervention increases in average velocity of play (m/min) to make up for a training week without game play. Finally, toward playoffs all athlete TD (m) were reduced, and practices shifted focus to low volume specific drills targeting set pieces. This proved to be successful for starters but limited contact time with the low-minute athlete group.

Conclusion

The purpose of this research was to identify if a GNSS and integrative IMU athlete tracking system could quantify potential exercise volume and intensity differences between high-minute (starters) and low-minute athletes (finishers and supporters). The GNSS system not only identified significant gaps between high-minute and low-minute athletes but also demonstrated the potential to inform an intervention targeted at improving within team development gaps for measures of exercise volume and intensity. Between athlete categories, it is likely that there will be gaps in TD (m) due to in game exposure time, and back-to-back in-season game schedules; however, successful interventions can minimize HSR- D (m) and R-HSR (m/min) gaps between high-minute and low-minute athletes without shifting the focus away from starters. This research intervention successfully improved supporter exercise volume and intensity, but there remains a need to focus on finisher athlete management to improve HSR-D (m) and R-HSR (m/min). Conducting a GNSS informed exercise volume and intensity intervention can improve development gaps and training differences between athlete categories, and potentially mitigate performance inequality, athlete dropout risk, and injury risk in low-minute athletes.

Appendix A

DALHOUSIE UNIVERSITY

Appendix A: Ethics Approval Form

REB File Number: 2023-6788
Project Title: Understanding the differences in exercise volume and intensity between high-minute and low-minute game exposure athletes - Determining how much participation is necessary to prepare athletes for game participation

Dear Ryan,

After review, the Health Sciences Research Ethics Board has determined that this project is exempt from REB oversight pursuant to article 2.5 of the Tri Council Policy Statement Ethical Conduct for Research Involving Humans. Good luck with your project.

Sincerely,
Catherine

Catherine Connors (she/her) | **Director Research Ethics** | **Dalhousie University**

DALHOUSIE UNIVERSITY

Appendix A: Recruitment Script

VOLUNTEERS WANTED FOR RESEARCH STUDYING:

DETERMINING HOW MUCH TRAINING IS NECESSARY TO PREPARE ATHLETES FOR GAME PARTICIPATION

A research study conducted by the Division of Kinesiology at Dalhousie University is looking for volunteers for a research study quantifying the training discrepancies between starters, secondary, and third team or red shirt athletes by examining exposure to volume and intensity in training and game play. Participants involved in the study will need to be varsity athletes on the Dalhousie Women's soccer program, this research study will be a program evaluation conducting a review of training and game collected data from the Dalhousie Women's Soccer Coaching Staff. Participation will be ongoing through the duration of the Women's soccer season from August 14th, 2023, to November 14th 2023.

Participation in this study is independent of the Dalhousie Athletics and Recreation department. Further use of data and athlete information beyond the athletic department will have student athlete data de-identified, anonymous, and only group aggregated data will be presented on.

Conditionings for Ongoing Evaluation:

Student athletes currently on the Dalhousie Women's Soccer Program roster will wear GPS and IMUs through training and game play.

You may be eligible to participate if you:

Play for the Dalhousie Women's Soccer program and are between the age of 17 and 28 years of age.

You will not be eligible to participate if you:

You must be an eligible varsity student athlete on the Dalhousie Women's soccer program, if you are ineligible to play or not on the Dalhousie women's soccer team you will not be eligible for this study.

You will be asked to report to the Dalplex High Performance room located in the Dalplex at 2360, South Street for more information about this study or to volunteer, please contact Dr. Ryan Frayne (Ryan.Frayne@dal.ca).

DALHOUSIE UNIVERSITY

Appendix A: Sample Email Script for Interested Participants

Dear, ,

Thank you for your interest in the study, "Determining how much training is necessary to prepare athletes for game participation", which is being conducted by Brett Armstrong and Dr. Ryan Frayne, an Instructor of Kinesiology from the School of Health, and Human Performance at Dalhousie University. We are investigating the training discrepancies between starters, secondary, and third team or red shirt athletes by examining exposure to volume and intensity in training and game play. Dalhousie University Women's Soccer program to ensure that lower minute athletes are physically prepared to step into a high minute athlete position without the fear of injury due to the sudden increase in exercise intensity and volume. Progressing towards a standardized approach to quantifying athlete volume and intensity through GPS use (2,3), improves training evaluations and informed practice to optimize performance. In order to participate in this study, you must be an eligible varsity athlete on the Dalhousie Women's Soccer team. We will review the questionnaire and the information within the letter of information to determine if you are eligible to continue with the study and to ensure you are comfortable participating. If you are determined to be ineligible to participate in the study, then please destroy these forms (i.e., shred hard copies, delete electronic copies).

You may be eligible to participate if you:

Student athletes currently on the Dalhousie Women's soccer program roster will wear GPS and IMUs through training and game play.

You will not be eligible to participate if you:

You must be an eligible varsity student athlete on the Dalhousie women's soccer program, if you are ineligible to play or not on the Dalhousie women's soccer team you will not be eligible for this study.

The research will be conducted on Dalhousie University Campus and inline with the programs schedule and team travel. Dalhousie University field and team training facilities will support both the site for data collection, student athlete training and competition. Athletes will be fitted with their own StatSports vest, GPS and IMU unit for the duration of the study. This study is ongoing from with pilot testing from August 14th, 2023 to November 14th, 2023 and formal data collection from August 14th, 2024 to November 14th, 2024. StatSports units will be turned on 30 minutes prior to training and placed in vests for athletes as they exit the training room to go on field.

We strongly recommend that you read all supplied information and please feel free to contact Dr. Ryan Frayne at Ryan.Frayne@dal.ca if you have any questions.

Thank you for your interest,

DALHOUSIE UNIVERSITY

Appendix A: Letter of Information and Informed Consent Document

Letter of Information and Informed Consent Document

Project title: Determining how much participation is necessary to prepare athletes for game participation.

You are invited to take part in a Mitacs Accelerative Funded research study being conducted by Dr. Ryan Frayne, an Instructor of Kinesiology from the School of Health and Human Performance at Dalhousie University. Your participation in this study is voluntary and you may withdraw from the study at any time without any repercussions to your studies or employment. The information below tells you about what you will be asked to do for the study and about any benefit, risk, or discomfort that you might experience.

Who will be conducting the research?

The principal investigator will be Dr. Ryan Frayne from the school of Health and Human Performance at Dalhousie University. Dr. Frayne can be contacted via email Ryan.Frayne@dal.ca or telephone at (902) 494-6499 should you have any questions or concerns about the study. The lead graduate researcher, Mr. Brett Armstrong, will be assisting and conducting data collection and analysis.

Introduction

We invite you to take part in this research study being conducted by, Dr. Ryan Frayne an instructor of Kinesiology, Mr. Brett Armstrong a graduate researcher at Dalhousie University. Choosing whether or not to take part in this research is entirely your choice. There will be no impact on [your studies/your employment/your performance evaluation/the services you receive] if you decide not to participate in the research. The information below tells you about what is involved in the research, what you will be asked to and about any benefit, risk, inconvenience, or discomfort that you might experience.
You should discuss any questions you have about this study with Dr. Ryan Frayne. Please ask as many questions as you like. If you have questions later, please contact Dr. Ryan Frayne.

Purpose and Outline of the Research Study

Currently, many Coaches and Sport scientists in the Atlantic University Sport (AUS) do not have an understanding of the exercise training volume and intensity differences that may exist between high minute (starters) and low minute (finishers/supports) athletes. This poses a problem because low minute athletes may be susceptible to injury when they are called upon to regularly participate in games and practice (3). For example, in professional athletics, poor exercise management accounted for 42% of illnesses and 40% of injuries (13) and could be explained by preceding spikes in training load. Global positioning sensors (GPS), combined with inertial measurement units (IMU), have been used extensively in sport, specifically in soccer (1-2,4-7), and can be used to track athlete exercise volume and intensity; permitting individualized training programs that may be used to minimize the incidence of injury in athletes.

Progressing towards a standardized approach to quantifying athlete volume and intensity through GPS use (10,11), improves training evaluations and informs practice strategy to optimize athletic performance. GPS and IMUs permit the direct measurement of a soccer players' external match and practice demands (15) which can be used to classify an athlete's performance and their maximum sustainable training volume and intensity (19). Doyle et al. 2021 used GPS to track position, velocity, and distance in international play. Analysis of total distance averages for athletes competing the whole game were 9389 +/- 368m (1), which is like other international women's soccer cohorts accumulating 8km to 11km, at 10.1 km average per match (7,20). Research in University sport assessed full match demands for NCAA Division I - III and it was identified that athletes covered an average total distance of 8.8km to 9.9km (20), with similar movement rates at 100 – 110 m/min in U Sports (4,18). These studies have outlined the match demands within professional and collegiate women's soccer (1-21); however, these studies have not identified how training volume and intensity varies across high game exposure athletes (starters), and those athletes with low game exposure. Therefore, the *general objective* of this research is to use GPS athlete tracking to quantify and determine if there are exercise volume and intensity differences that occur from in-game and practice exposures between starter, finisher, and supporting athletes on an Atlantic University Sport Women's Soccer Team. This study also aims to identify if there are any tactical exposure differences that occur between starter, finisher and supporter athletes.

This study will be conducted in accordance with Dalhousie Women's Soccer's team schedule, on site at Dalhousie University and at all the team's travel games. Therefore, the purpose of this study is to determine the training discrepancies between starters, secondary, and third team or red shirt athletes by examining exposure to volume and intensity in training and game play.

Who Can Take Part in the Research Study

You may participate in this study if you are an eligible varsity student athlete on the Dalhousie Women's soccer program, between the ages of 17 and 28 years of age.

You will NOT participate in this study if you:

If you are not an eligible varsity student athlete on the Dalhousie Women's soccer program, if you are ineligible to play or not on the Dalhousie women's soccer team you will not be eligible for this study.

What You Will Be Asked to Do?

Student athletes that choose to participate in this study will not be asked to do anything greater than what is already planned for the Women's varsity soccer team at Dalhousie University. The newly implemented GPS/IMU sensors and the Spiideo Field mounted camera system will be part of everyday athlete exercise and tactical exposure time monitoring, respectively. Although these are newly implemented technology for the team, the athletes will not be asked to do anything different from their general practice schedule or games.

Upon arrival to training camp and team meetings, student athletes will be provided with time to read the letter of information and provided with informed consent (in accordance with Dalhousie's Research Ethics Board) prior to the start of training camp activities. Students will be reminded that this is a program evaluation where we are conducting ongoing assessment through the duration of the competition season for the Dalhousie Women's soccer program. This study will not interfere with on field training or team training procedures, student athletes wearing GPS and IMU units will participate in normal team activities.

After consent is given student athletes will be briefed on use of GPS and IMU wearable devices for training. Team set-up, tear down, and student roles and expectations will be outlined. There are two periods of data collection for this study. In sub-objective one (2023-2024 season) athletes will be asked to diligently wear their StatSports GPS vest outfitted with a GPS unit during practices and games (as mentioned above something that is expected of them as a varsity athlete). At the completion of the season athletes will be asked to complete a short questionnaire asking about the feasibility of the GPS/IMU system and if there are ways to improve managing that application of the sensors with the athletes for games and practices. In sub-objective 2 (2024-2025 season), athletes will again be asked to diligently wear their sensors. Exercise data extracted from the GPS/IMU sensors and any discrepancies from year 1 of the study will be shared with the coaching staff to adjust athlete training in an attempt to equalize training for all levels of athlete. This may result in athletes being required to do slightly more tactical or physical training to ensure they are being trained up to the level of a starting athlete. Overall, the athletes are not being asked to do anything greater than what is expected of them as a Dalhousie University varsity women's soccer athlete. This project merely requires access to their GPS/IMU and tactical game play data to identify potential differences.

Possible Benefits, Risks and Discomforts
There is no direct benefit to participating in this study. Your participation will provide integral information for Kinesic Sport Labs and Dalhousie University regarding improved training evaluations and informed practice to optimize performance in women's soccer. This is a program evaluation study, there will be no change to current team environment or limitation to training. Student athletes will be fulling participating in daily training activities without disruption and due to there being no change to current team environments there is little injury risk associated with participating in this study. Participation in this study will not involve any intervention or change to current sport performance or participation for the student athlete who is already eligible and selected to compete on the Dalhousie Women's soccer team.

Compensation / Reimbursement
There is no compensation or reimbursement for participation in this study.

How your information will be protected:
Information that you provide us will be kept private. Only the research team working on this research project at Dalhousie University will have access to this information. We may describe

and share our group findings in oral and/or poster presentations at conferences or seminars. We will also submit our anonymous and aggregated group findings for publication to an academic journal. The aggregated group findings may also be presented to Kinesic Sport Labs and Dalhousie Athletics and Recreation. We will ensure that no subject is identified during any dissemination of this research. This means that ***you will not be identified in any way in our reports and presentations.*** The people who work with your information have special training and have an obligation to keep all research information private. Also, we will use participant number (not your name) in our written and computerized records so that the information we have about you contains no identifiers (ie. name, age, sex, etc.). All your identifying information will be kept in a separate file, in a locked cabinet, in a locked room in the Dalplex. All electronic records will be kept secure in a password-protected, encrypted file on the researcher's laboratory computer (or on a Dalhousie University secure server).

If You Decide to Stop Participating
You are free to leave the study at any time. If you decide to stop participating at any point in the study, you can also decide whether or not to have any information/data obtained to that point destroyed. You may decide to have your information and data removed up to 1 month after your day of testing. After that time, it will be incorporated into the group results and analyzed.

How to Obtain Results?
You can obtain either group results or your individual results by including your contact information at the end of the signature page and selecting one of the following result options; Group results, Individual results (ie. Your results), Both, or Neither. Dr. Frayne will send your desired results to you via your preferred method.

Questions
We are happy to talk with you about any questions or concerns that you may have about your participation in this research study. Please contact Dr. Ryan Frayne at (Ryan.Frayne@dal.ca) or (902) 494-6499, at any time. We will also tell you if you if any new information comes up that could affect your decision to participate.

If you have any ethical concerns about your participation in this research, you may also contact Catherine Connors, Director, Research Ethics, Dalhousie University at (902) 494-1462, or email: ethics@dal.ca

DALHOUSIE UNIVERSITY

Consent for participation in the research study
Signature Page

Project Title: Determining how much participation is necessary to prepare athletes for game participation.

Lead Researcher: Dr. Ryan Frayne, Instructor of Kinesiology from the School of Health, and Human Performance at Dalhousie University, Ryan.Frayne@dal.ca

I,_____________________ have read the explanation about this study. I have been given the opportunity to discuss it and my questions have been answered to my satisfaction. I agree to take part in this study. My participation is voluntary and I understand that I am free to withdraw from the study at any time, until one month following the completion of the study.

____________________________ ____________________________ ___________"

Name Signature Date

Do you consent to using di-identified information of you for publication, presentation, or reports? All information conducted in the research study would be de-identified, please sign below if you consent to using your de-identified information.

____________________________ ____________________________ ___________"

Name Signature Date

Please send me (please circle):

Group Results	**Individual Results**	**Both**	**Neither**

Please contact me at (please list a phone number, email address, or mailing address):
Phone Number: _______________________________
E- mail Address: _______________________________
Mailing Address: _______________________________

Person obtaining consent (Researcher)

I confirm that I have explained the nature and purpose of the study to the participant named above and have answered all questions. In my judgement the participant is voluntarily and knowingly giving informed consent to participate in this research study.

____________________________ ___________"

Signature Date

Appendix B

Appendix B: Figures and Tables

Table 1

Mean Weekly Total Distance (m), Supporter (Intercept)

Mean Weekly Total Distance for Supporter (Intercept)

Competition Categories	*Average Weekly Total Distance (m)*	*Mean Differences (MD)*	*CI*	*P*
Intercept (Supporters, Phase I, Pilot Training Period)	9,220.51	-	-358.42 – 18799.44	0.059
Finishers Phase I, Pilot Training Period	18,987.16	9,766.65	-3758.60 – 23291.90	0.156
Starters Phase I, Pilot Training Period	27,523.59	18,303.08	4870.95 – 31735.20	0.008
Phase II, Supporters				
Training Period [1]	19,724.07	10,503.56	5794.99 – 15212.13	< 0.001
Training Period [2]	22,050.52	12,830.01	8300.49 – 17359.54	< 0.001
Training Period [3]	20,983.37	11,762.86	6948.83 – 16576.89	< 0.001
Training Period [4]	14,259.12	5,038.61	105.69 – 9971.52	0.045
Training Period [5]	13,353.84	4,133.33	-249.68 – 8516.33	0.064
Random Effects				
σ^2		54500429.73		
$\tau_{00\ Competition\_Category}$		21616219.68		
ICC		0.28		
$N_{Competition\_Category}$		3		
Observations		353		
Marginal R^2 / Conditional R^2		0.385 / 0.560		

Note. Mean weekly total distance for supporter (Intercept): Mean weekly total distance for supporter (intercept) grouping, displaying differences against athlete categories in phase I pilot testing, and estimate mean differences for the supporter position grouping in training periods 1 -5.

Table 2

Mean Weekly Total Distance (m), Finisher (Intercept)

Mean Weekly Total Distance for Supporter (Intercept)

Competition Categories	*Average Weekly Total Distance (m)*	*Mean Differences (MD)*	*CI*	*P*
Intercept (Finishers, Phase I, Pilot Training Period)	18,987.16	-	9438.52 – 28535.80	< 0.001
Supporters Phase I, Pilot Training Period	9,220.51	-9,766.65	-23291.90 – 3758.60	0.156
Starters Phase I, Pilot Training Period	27,523.59	8,536.43	-4874.11 – 21946.96	0.211
Phase II, Finishers				
Training Period [1]	23,688.60	4,701.44	-172.39 – 9575.27	0.059
Training Period [2]	27,885.73	8,898.57	3731.00 – 14066.14	0.001
Training Period [3]	26,035.90	7,048.74	2174.91 – 11922.58	0.005
Training Period [4]	20,552.53	1,565.37	-3188.10 – 6318.85	0.518
Training Period [5]	17,310.85	-1,676.31	-6063.56 – 2710.95	0.453
Random Effects				
σ^2		54500429.73		
$\tau_{00\ Competition\_Category}$		21616220		
ICC		0.28		
$N_{Competition\_Category}$		3		
Observations		353		
Marginal R^2 / Conditional R^2		0.385 / 0.560		

Note. Mean weekly total distance for finisher (intercept) grouping, displayed in mean differences against athlete categories in phase I pilot testing, and estimate mean differences for the finisher position grouping in training periods 1-5.

Table 3

Mean Weekly High-Speed Running HSR-D (m), Supporter (Intercept)

Mean Weekly High Speed Running for Supporter (Intercept)

Competition Categories	*Average Weekly HSR (m)*	*Mean Differences (MD)*	*CI*	*P*
Intercept (Supporter, Phase I, Pilot Training Period)	421.3	-	-271.64 – 1114.25	0.233
Finishers Phase I, Pilot Training Period	1299.13	877.83	-98.02 – 1853.68	0.078
Starters Phase I, Pilot Training Period	2,006.79	1,585.49	627.69 – 2543.30	0.001
Phase II, Supporters				
Training Period [1]	2,096.44	1,675.14	1120.02 – 2230.25	<0.001
Training Period [2]	2,575.07	2,153.77	1619.76 – 2687.77	<0.001
Training Period [3]	1,774.41	1,353.11	785.57 – 1920.66	<0.001
Training Period [4]	695.60	274.3	-307.26 – 855.86	0.354
Training Period [5]	1,091.71	670.41	153.68 – 1187.14	0.011
Random Effects				
σ^2		757503.37		
$\tau_{00\ Competition\_Category}$		94955.29		
ICC		0.11		
$N_{Competition\_Category}$		3		
Observations		353		
Marginal R^2 / Conditional R^2		0.330 / 0.405		

Note. Mean weekly high-speed running (HSR-D m) for supporter (intercept) grouping, displayed in mean differences against athlete categories in phase I pilot testing, and estimate mean differences for the finisher position grouping in training periods 1-5.

Table 4

Mean Weekly Average Velocity (m/min), Supporter (Intercept)

Mean Weekly Metres Per Minute for Supporter (Intercept)

Competition Categories	*Average Weekly m/min*	*Mean Differences (MD)*	*CI*	*P*
Intercept (Supporter, Phase I, Pilot Training Period)	48.02	-	29.68 – 66.35	< 0.001
Finishers Phase I, Pilot Training Period	41.87	-6.15	-32.06 – 19.76	0.641
Starters Phase I, Pilot Training Period	54.90	6.88	-18.96 – 32.72	0.601
Phase II, Supporters				
Training Period [1]	48.52	0.5	-5.35 – 6.35	0.867
Training Period [2]	44.78	-3.24	-8.87 – 2.39	0.258
Training Period [3]	48.41	0.39	-5.59 – 6.38	0.897
Training Period [4]	56.09	8.07	1.94 – 14.20	0.01
Training Period [5]	46.76	-1.26	-6.71 – 4.18	0.648
Random Effects				
σ^2		84.16		
$\tau_{00\ Competition\_Category}$		83.64		
ICC		0.5		
$N_{Competition\_Category}$		3		
Observations		353		
Marginal R^2 / Conditional R^2		0.223 / 0.610		

Note. Mean weekly average velocity (m/min) for supporter (intercept) grouping, displayed in mean differences against athlete categories in phase I pilot testing, and estimate mean differences for the finisher position grouping in training periods 1-5.

Table 5

Mean Weekly Rate of High-Speed Running (R-HSR m/min), Supporter (Intercept)

Mean Weekly High Speed Running for Supporter (Intercept)				
Competition Categories	*Average Weekly HSR (m/min)*	*Mean Differences (MD)*	*CI*	*P*
Intercept (Supporter, Phase I, Pilot Training Period)	2.26	-	1.58 – 2.94	<0.001
Finishers Phase I, Pilot Training Period	2.83	0.57	-0.37 – 1.51	0.232
Starters Phase I, Pilot Training Period	4.01	1.75	0.87 – 2.62	<0.001
Phase II, Supporters				
Training Period [1]	5.14	2.88	1.85 – 3.91	<0.001
Training Period [2]	5.18	2.92	1.93 – 3.91	<0.001
Training Period [3]	4	1.74	0.69 – 2.80	0.001
Training Period [4]	2.55	0.29	-0.79 – 1.37	0.598
Training Period [5]	3.94	1.68	0.72 – 2.64	0.001
Random Effects				
σ^2	2.61			
$\tau_{00\ Competition\_Category}$	0.02			
ICC	0.01			
$N_{Competition\_Category}$	3			
Observations	353			
Marginal R^2 / Conditional R^2	0.251 / 0.256			

Note. Mean weekly rate of high-speed running meters per minute (R-HSR: m/min) for supporter (intercept) grouping, displayed in mean differences against athlete categories in phase I pilot testing, and estimate mean differences for the finisher position grouping in training periods 1- 5.

Table 6

Phase II Tactical Exposure Total Time

Small Sided Games *(SSG)*				
	Total Time (min)	Mean Difference (MD)	*CI*	*p*
Supporter *(Intercept)*	594.06	-	3.71 – 1184.41	0.049
Finisher	722.33	128.27	-712.22 – 968.77	0.76
Starter	1089.53	495.47	-342.06 – 1333.01	0.24
Medium Sided Games *(MSG)*				
	Total Time (min)	Mean Difference (MD)	*CI*	*p*
Supporter *(Intercept)*	590.9	-	341.22 – 840.58	<0.001
Finisher	585.85	-5.05	-373.51 – 363.41	0.978
Starter	690.59	99.69	-245.60 – 444.99	0.564
Large Sided Games *(LSG)*				
	Total Time (min)	Mean Difference (MD)	*CI*	*p*
Supporter *(Intercept)*	256.18	-	78.00 – 434.35	0.006
Finisher	142.86	-113.32	-367.26 – 140.63	0.373
Starter	170.1	-86.08	-339.28 – 167.13	0.496
Live Game Play *(Match Day)*				
	Total Time (min)	Mean Difference (MD)	*CI*	*p*
Supporter *(Intercept)*	60.27	-	-808.57 – 929.11	0.888
Finisher	672.29	612.0	-585.47 – 1809.52	0.305
Starter	1,089.25	1,028.98	-168.52 – 2226.48	0.089

Note. Displays four drill classifications: Small Sided Games, Medium Sided Games, Large Sided Games, and Live Game Play for Phase II. The athlete categories are compared using supporters set as the intercept for each linear model. Total time (minutes) represents each athlete categories time spent in each tactical drill.

References

1. Blanch P, Gabbett TJ. Has the athlete trained enough to return to play safely? The acute:chronic workload ratio permits clinicians to quantify a player's risk of subsequent injury. Br J Sports Med. 2016 Apr;50(8):471–5.

2. Piggott B, Newton M, Mcguigan M. The relationship between training load and incidence of injury and illness over a pre-season at an Australian Football League Club. ECU Publ. 2009 Jan 1;17.

3. Olthof SBH, Frencken WGP, Lemmink KAPM. When something is at stake: differences in soccer performance in 11 vs. 11 during official matches and training games. J Strength Cond Res. 2019 Jan;33(1):167.

4. Clemente FM, Owen A, Serra-Olivares J, Nikolaidis PT, van der Linden CMI, Mendes B. Characterization of the weekly external load profile of professional soccer teams from Portugal and the Netherlands. J Hum Kinet. 2019 Mar 27;66:155–64.

5. Cummins C, Orr R, O'Connor H, West C. Global positioning systems (GPS) and microtechnology sensors in team sports: a systematic review. Sports Med. 2013;43(10):1025–42.

6. Akenhead R, French D, Thompson KG, Hayes PR. The acceleration dependent validity and reliability of 10 Hz GPS. J Sci Med Sport. 2014;17(5):562–6.

7. Rave G, Granacher U, Boullosa D, Hackney A, Zouhal H. How to use global positioning systams (GPS) data to monitor training load in the "real world" of elite soccer. Front Physiol. 2020;2(11):1–11.

8. Taberner M, Allen T, Cohen DD. Progressing rehabilitation after injury: consider the "control-chaos continuum." Br J Sports Med. 2019 Sep;53(18):1132–6.

9. Delves RIM, Duthie GM, Ball KA, Aughey RJ. Applying common filtering processes to global navigation satellite system-derived acceleration during team sport locomotion. J Sports Sci. 2022 May;40(10):1116–26.

10. Ramos GP, Nakamura FY, Penna EM, Wilke CF, Pereira LA, Loturco I, et al. Activity profiles in U17, U20, and Senior Women's Brazilian National Soccer teams during international competitions: Are There Meaningful Differences? J Strength Cond Res. 2019 Dec;33(12):3414–22.

11. Doyle B, Browne D, Horan D. Quantification of internal and external training load during a training camp in senior international female footballers. Sci Med Footb. 2022 Feb;6(1):7–14.

12. Gabbett TJ. The development of a test of repeated-sprint ability for elite women's soccer players. J Strength Cond Res. 2010 May;24(5):1191–4.

13. Hooper SL, Mackinnon LT. Monitoring overtraining in athletes. Recommendations. Sports Med Auckl NZ. 1995 Nov;20(5):321–7.

14. Mccall A, Lewin C, O'Driscoll G, Witvrouw E, Ardern C. Return to play: the challenge of balancing research and practice. Br J Sports Med. 2016 Sep 15;51:bjsports-2016.

15. Mclean B, Coutts A, Kelly V, McGuigan M, Cormack S. Neuromuscular, endocrine, and perceptual fatigue responses during different length between-match microcycles in professional rugby league players. Int J Sports Physiol Perform. 2010 Sep 1;5:367–83.

16. Petrigna L, Pajaujiene S, Delextrat A, Gómez-López M, Paoli A, Palma A, et al. The importance of standard operating procedures in physical fitness assessment: a brief review. Sport Sci Health. 2022 Mar 1;18(1):21–6.

17. Strauss A, Sparks M, Pienaar C. The use of GPS analysis to quantify the internal and external match demands of semi-elite level female soccer players during a tournament. J Sports Sci Med. 2019 Feb 11;18(1):73–81.

18. Varley MC, Fairweather IH, Aughey RJ. Validity and reliability of GPS for measuring instantaneous velocity during acceleration, deceleration, and constant motion. J Sports Sci. 2012;30(2):121–7.

19. Kavanagh R, McDaid K, Rhodes D, McDonnell J, Oliveira R, Morgans R. An analysis of positional generic and individualized speed thresholds within the most demanding phases of match play in the English Premier League. Int J Sports Physiol Perform. 2023 Dec 21;19(2):116–26.

20. Gualtieri A, Rampinini E, Dello Iacono A, Beato M. High-speed running and sprinting in professional adult soccer: Current thresholds definition, match demands and training strategies. A systematic review. Front Sports Act Living [Internet]. 2023 [cited 2023 Dec 3];5. Available from: https://www.frontiersin.org/articles/10.3389/fspor.2023.1116293

21. Cormier P, Meylan C, Agar-Newman D, Geneau D, Epp-Stobbe A, Lenetsky S, et al. A Systematic review and meta-analysis of wearable satellite system technology for linear sprint profiling: technological innovations and practical applications. J Strength Cond Res. 2023 Oct 20;

22. Bortnik L, Bruce-Low S, Burger J, Alexander J, Harper D, Morgans R, et al. Physical match demands across different playing positions during transitional play and high-pressure activities in elite soccer. Biol Sport. 2023;41(2):73–82.

23. Furtado Mesa M, Stout JR, Redd MJ, Fukuda DH. Accumulated workload differences in collegiate women's soccer: starters versus substitutes. J Funct Morphol Kinesiol. 2023 Jun 12;8(2):78.

24. Park LAF, Scott D, Lovell R. Velocity zone classification in elite women's football: where do we draw the lines? Sci Med Footb. 2019 Jan 2;3(1):21–8.

25. Akenhead R, Nassis GP. Training load and player monitoring in high-level football: current practice and perceptions. Int J Sports Physiol Perform. 2016 Jul;11(5):587–93.

26. Hewitt A, Norton K, Lyons K. Movement profiles of elite women soccer players during international matches and the effect of opposition's team ranking. J Sports Sci. 2014 Dec;32(20):1874–80.

27. Vescovi JD, Fernandes E, Klas A. Physical demands of women's soccer matches: a perspective across the developmental spectrum. Front Sports Act Living [Internet]. 2021 Apr;16(3):634696

28. Bortnik L, Nir O, Forbes N, Alexander J, Harper D, Bruce-Low S, et al. Worst case scenarios in soccer training and competition: analysis of playing position, congested periods, and substitutes. Res Q Exerc Sport. 2023;0(0):1–13.

29. Owen A, Peñas C, Ruano M, Mendes B, A D. Analysis of a training mesocycle and positional quantification in elite European soccer players. Int J Sports Sci Coach. 2017 Oct 1;12:1–8.

30. Sydney MG, Ball N, K. Mara J, Chapman D, Wollin M. Substitute running outputs in elite youth male soccer players: less peak but greater relative running outputs. Biol Sport. 2022;40(1):241–8.

31. Aalbers B, Van Haaren J. Distinguishing between roles of football players in play-by-play match event data. In 2019. p. 31–41.

32. Turczyn D, McMillan D, Gardiner PF, Cornish SM. Does sleep quality between back-to-back matches influence running performance in Canadian female university soccer players? A GPS-based time-series analysis. Int J Kinesiol Sports Sci. 2022 Jan 30;10(1):9–17.

33. Gabbett TJ, Kennelly S, Sheehan J, Hawkins R, Milsom J, King E, et al. If overuse injury is a "training load error", should undertraining be viewed the same way? Br J Sports Med. 2016 Sep;50(17):1017.

34. Taberner M, van Dyk N, Allen T, Jain N, Richter C, Drust B, et al. Physical preparation and return to performance of an elite female football player following ACL reconstruction: a journey to the FIFA Women's World Cup. BMJ Open Sport Exerc Med. 2020;6(1):e000843.

35. Watson K. The experiences of athletes, parents, and coaches with the long-term athlete development model (LTAD) in youth soccer academies [Masters Thesis]. Wilfrid Laurier University; 2017.

36. Lambert M, Borresen J. Measuring training load in sports. Int J Sports Physiol Perform. 2010 Sep 1;5:406–11.

37. Kim M, Park C, Yoon J. The design of GNSS/IMU loosely-coupled integration filter for wearable EPTS of football players. Sensors. 2023 Feb 4;23(4):1749.

38. Crang ZL, Duthie G, Cole MH, Weakley J, Hewitt A, Johnston RD. The validity of raw custom-processed global navigation satellite systems data during straight-line sprinting across multiple days. J Sci Med Sport. 2024 Mar 1;27(3):204–10.

39. Crang ZL, Duthie G, Cole MH, Weakley J, Hewitt A, Johnston RD. The inter-device reliability of global navigation satellite systems during team sport movement across multiple days. J Sci Med Sport. 2022;25(4):340–4.

40. Crang ZL, Duthie G, Cole MH, Weakley J, Hewitt A, Johnston RD. The validity and reliability of wearable microtechnology for intermittent team sports: a systematic review. Sports Med. 2021;51(3):549–65.

41. Beato M, Coratella G, Stiff A, Iacono AD. The validity and between-unit variability of GNSS Units (STATSports Apex 10 and 18 Hz) for measuring distance and peak speed in team sports. Front Physiol. 2018;9:1288.

42. Bertschy M, Howard JT, Oyama S, Cheever K. Reduced injury prevalence in soccer athletes following GPS guided acclimatization. Int J Exerc Sci. 2021 Aug 1;14(7):1070–7.

43. Guitart M, Casals M, Casamichana D, Cortés J, Valle FX, McCall A, et al. Use of GPS to measure external load and estimate the incidence of muscle injuries in men's football: A novel descriptive study. PloS One. 2022;17(2):e0263494.

44. Carling C, Bradley P, McCall A, Dupont G. Match-to-match variability in high-speed running activity in a professional soccer team. J Sports Sci. 2016 Dec;34(24):2215–23.

45. Ju W, Doran D, Hawkins R, Evans M, Laws A, Bradley P. Contextualised high-intensity running profiles of elite football players with reference to general and specialised tactical roles. Biol Sport. 2022;40(1):291–301.

46. Beato M, de Keijzer KL. The inter-unit and inter-model reliability of GNSS STATSports Apex and Viper units in measuring peak speed over 5, 10, 15, 20 and 30 meters. Biol Sport. 2019;36(4):317–21.

47. Bataller-Cervero AV, Gutierrez H, DeRentería J, Piedrafita E, Marcén N, Valero-Campo C, et al. Validity and reliability of a 10 Hz GPS for assessing variable and mean running speed. J Hum Kinet. 2019;67:17–24.

48. Scott D, Norris D, Lovell R. Dose-response relationship between external load and wellness in elite women's soccer matches: do customized velocity thresholds add value? Int J Sports Physiol Perform. 2020 Oct 1;15(9):1245–51.

49. Costa JA, Rago V, Brito P, Figueiredo P, Sousa A, Abade E, et al. Training in women soccer players: a systematic review on training load monitoring. Front Psychol [Internet]. 2022 Jul 29;13:943857

50. Baker D, Heany N. Practical examples of the implementation of high-intensity aerobic energy system conditioning methods for field sports. J Aust Strength Cond. 2015;23(7):60–7.

51. Malone JJ, Lovell R, Varley MC, Coutts AJ. Unpacking the black box: applications and considerations for using GPS devices in sport. Int J Sports Physiol Perform. 2017 Apr;12(Suppl 2):S218–26.