



Application of Global Positioning System Technology and Machine Learning to Characterise the Activity Profile of Elite Gaelic Football Referees

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DECLARATION

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IN LOVING MEMORY OF

Bridget 'Biddy' McMackin

1937 – 2020

“Ní bheidh a leithéid arís ann”

PEER-REVIEWED PUBLICATIONS AND CONFERENCE PROCEEDINGS

Publications

Brady AJ, Scriney M, Moyna NM, McCarren A. Identification of movement categories and associated velocity thresholds for elite Gaelic football and hurling referees. *Int J Perform Anal Sport*. 2021;21(5):741–53.

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LIST OF ABBREVIATIONS

AIC	All-Ireland Championship
AIQ	All-Ireland Qualifiers
AIS	All-Ireland Series
ASR	Anaerobic speed reserve
BMI	Body mass index
CBT	Computer-based tracking
CI	Confidence interval
CP	Critical power
CV	Coefficient of variation
EMM	Estimated marginal mean
ES	Effect size
FBLC	Fixed blood lactate concentration
FIFA	Fédération Internationale de Football Association
GAA	Gaelic Athletic Association
GET	Gas exchange threshold
GFR	Gaelic football referee
GNSS	Global navigation satellite system
GPS	Global positioning system
HDOP	Horizontal dilution of precision
HIA	High-intensity activity
HIR	High-intensity running
HR	Heart rate
HR _{max}	Maximal heart rate
HSR	High-speed running
ICC	Intraclass correlation coefficient
IFTS	Invasion field-based team sport
LMM	Linear mixed model

LSR	Low-speed running
LT	Lactate threshold
MAS	Maximal aerobic speed
MLSS	Maximal lactate steady state
MSR	Moderate-speed running
MSS	Maximal sprint speed
NFL	National Football League
RCP	Respiratory compensation point
RE	Running economy
RPE	Rating of perceived exertion
SD	Standard deviation
SE	Standard error
SEE	Standard error of estimate
SEM	Standard error of measurement
SoS	Sum of squares
TEM	Technical error of measurement
TMA	Time motion analysis
$\dot{V}CO_2$	Carbon dioxide production
$\dot{V}E$	Minute ventilation
$\dot{V}E/\dot{V}CO_2$	Ventilatory equivalent for carbon dioxide
$\dot{V}E/\dot{V}O_2$	Ventilatory equivalent for oxygen
VHSR	Very high-speed running
VIF	Variance inflation factor
VLSM	Very low-speed movement
$\dot{V}O_2$	Oxygen uptake
$\dot{V}O_{2max}$	Maximal oxygen uptake
VT	Ventilatory threshold
$v\dot{O}_{2max}$	Velocity at maximal oxygen uptake
YIRT1	Yo-Yo Intermittent recovery test Level 1

ABSTRACT

Aidan Brady

Application of Global Positioning System Technology and Machine Learning to Characterise the Activity Profile of Elite Gaelic Football Referees

Gaelic football is officiated by a referee whose decisions can influence the outcome of the game. To ensure optimal positioning for decision making, Gaelic football referees (GFR) must keep up with play at all times which poses a considerable physical challenge. Currently no data are available on the activity profile of GFR during match play.

Study 1 applied a two-stage unsupervised clustering technique to activity data to generate a set of unique movement category velocity thresholds for elite GFR. The activity data were collected during 338 All-Ireland Championship (AIC) and National Football League (NFL) games using 10 Hz global positioning system technology. The newly generated thresholds were more strongly associated with the raw velocity data and resulted in a significant difference in the distribution of the total distance in comparison to arbitrary thresholds.

Study 2 and Study 3 examined the activity profile and temporal changes of elite GFR during 206 AIC and 132 NFL games, respectively, using the newly generated movement categories. During both AIC and NFL games, the relative distance and the distance covered in each movement category, except very high-speed running, was significantly different between halves. The first quarter was the most intense period of the game with a significantly greater relative and high-speed running (HSR) distance compared to any other quarter of match play. There were minimal differences in the activity profile between the three phases of the AIC and the four divisions of the NFL.

Study 4 compared the activity profile of elite GFR between the NFL and AIC, and examined the influence of age, experience, and aerobic fitness on the activity profile during both competitions. Games in the AIC were significantly longer in duration but minimal difference was found in the activity profile between NFL and AIC games. Relative and HSR distance during AIC games was influenced by aerobic fitness level. Age and experience level did not influence the activity profile during NFL or AIC games.

In summary, this research generated a unique set of velocity-based movement categories that are specific to elite GFR. These categories facilitated the detailed characterisation of the activity profile of elite GFR during both NFL and AIC games. It is envisaged that this information will assist in the design of sport specific conditioning programmes for elite GFR.

CHAPTER I

INTRODUCTION

1.1 Background

The Gaelic Athletic Association (GAA), the largest sporting organisation in Ireland, was established in 1884 with the aim of promoting the traditional Irish games of Gaelic football, hurling, handball and rounders. The GAA is recognised as the largest amateur sporting organisation in the world with more than 2,000 affiliated clubs in Ireland and 400 internationally (1). Of the sports promoted by the GAA, Gaelic football is the most popular (2).

Gaelic football is an intermittent invasion field-based team sport (IFTS). It is played between two teams comprising 15 players each, on a playing area measuring approximately 130 – 145 m x 80 – 90 m (3). Similar to other IFTS such as soccer and Australian football, Gaelic football involves brief periods of high-speed activity interspersed with low-speed activity, performed over two 35 min halves. The periods of high-speed activity are unpredictable, influenced by the patterns of play and can vary greatly from one game to another (4).

Competitions in Gaelic football are organised at both sub-elite club level and elite inter-county level. Inter-county teams comprise the top-rated club players within each county. The National Football League (NFL) and the All Ireland Championship (AIC) are the two major inter-county competitions. A referee with assistance from two side-line officials and four goal-line umpires officiate inter-county games. Consistent with other IFTS, decisions of the referee have the potential to influence the outcome of the game. To

ensure optimal positioning for decision making, referees are required to keep up with play, irrespective of game tempo. Refereeing at the elite level in Gaelic football therefore represents a considerable physical challenge especially as the relative playing area in Gaelic football (~440 m²) is much greater than in other popular IFTS such as soccer (~320 m²), rugby (~233 m²) or field hockey (~228.5 m²).

Recent advances in global positioning systems (GPS) technology have facilitated the non-invasive evaluation of the activity profile of IFTS athletes during training and competition (5). Many GPS units are also compatible with real time telemetry-based physiological monitoring systems enabling the simultaneous collection of heart rate (HR) and respiratory rate. GPS data are routinely used by coaches to identify key performance indicators and by athletic development coaches to optimise conditioning programmes (6).

Activity data derived from GPS technology include total distance along with distance covered in a number of velocity-based movement categories. Each category is typically assigned a verbal descriptor such as low, moderate or high-speed (7). Among elite Gaelic football players, examination of the total distance and distance covered in a number of movement categories has identified distinct positional differences in running performance and revealed time-dependent reductions in running performance across match halves and quarters (8, 9). Studies have also investigated the influence of contextual factors on the activity profile of elite Gaelic football players and found differences between the phase of the season and standard of competition (10–12). To date, no studies have examined the activity profile of elite Gaelic football referees (GFR).

Several studies have examined the activity profile of soccer referees across various levels of competition (13). Despite being 10 – 15 years older than players, elite soccer referees cover similar total and high-speed running (HSR) distances to elite players during match play and elicit a comparable HR response (13). Evidence of temporal changes in the activity profile of elite soccer referees during competitive games has also been reported. Most notably, referees were found to be positioned further from infringements during the latter stages of games and were more likely to make incorrect decisions in the second half (14–16).

1.2 Statement of the problem

Despite their important officiating role, there is currently no published research examining the activity profile of elite GFR. This lack of information is a major limitation in the design and implementation of specific conditioning programmes for GFR. Research examining the activity profile of referees in other IFTS such as soccer and rugby have typically used arbitrary movement category velocity thresholds designed for players. These thresholds may not be appropriate for use with referees due to differences in physical capacity with players (17, 18). Finally, the influence of contextual factors such as age, experience, and physical fitness on the activity profile of elite GFR is currently unknown.

1.3 Study purpose

The purpose of this thesis is to identify movement categories and associated velocity thresholds for elite GFR and to assess their activity profile during inter-county games.

1.4 Study aims

1. To identify movement categories and associated velocity thresholds for elite GFR
2. To describe the activity profile of elite GFR during NFL and AIC games
3. To examine temporal changes in the activity profile of elite GFR during NFL and AIC games
4. To examine the effect of competitive level and phase of competition on the activity profile of elite GFR during NFL and AIC games
5. To examine the influence of age, refereeing experience and aerobic fitness on the activity profile of elite GFR during NFL and AIC games

1.5 Study hypothesis

1. The movement categories generated for elite GFR will be different to the categories commonly used in the analysis of both IFTS players and referees
2. The majority of the distance covered by elite GFR during NFL and AIC games will be at low and moderate speeds
3. There will be a time-dependent reduction in total and HSR distance between match halves and across the four quarters for elite GFR during both NFL and AIC games
4. There will be a significant difference in the activity profile of elite GFR between playing divisions in the NFL and no difference between the provincial championships and All-Ireland Series (AIS)
5. Age, experience level, and aerobic fitness will have a significant impact on the activity profile of elite GFR during NFL and AIC games

CHAPTER II

LITERATURE REVIEW

2.1 The Gaelic Athletic Association

The GAA was founded in 1884 with the goal of promoting the Gaelic games of Gaelic football, hurling, handball and rounders with sister organisations to promote Ladies Gaelic football and camogie. Today, the GAA is the largest sporting organisation in Ireland with 2,200 affiliated clubs. In addition, more than 400 clubs have been established outside of Ireland (1). Of the games promoted by the GAA, Gaelic football is the most popular (2). Children up to the age of 11 years participate in non-competitive 'Go Games' with competitive competitions commencing at age 12 and progressing through to senior level. GAA clubs are organised around the traditional parishes and counties of Ireland. Outstanding club level players are selected to represent their county team, referred to as inter-county, which is the elite level within Gaelic football.

2.1.1 Characteristics of Gaelic football

Gaelic football is a dynamic, IFTS played by two teams of 15 players (19). It is often described as a hybrid of soccer, Australian football and rugby. Gaelic football involves brief periods of high-speed activity interspersed with low and moderate-speed physical activity (20). The activity patterns are imposed by the pattern of play and can vary greatly in duration, from player to player, and from game to game (8). Games are played on a rectangular grass surface measuring 80 – 90 m in width and 130 – 145 m in length (Figure [2.1](#)). The match ball is of similar size and shape to soccer but is slightly heavier (21). The primary objective of the game is to outscore the opposing team. A set of 'H' shaped

goalposts consisting of two uprights 6.5 m apart and a crossbar 2.5 m from the ground are located in the centre of each end line. A point is awarded when the ball crosses the end line between the two uprights and above the crossbar and a goal, worth 3 points, is awarded when the ball crosses the end line between the two uprights and below the crossbar. Players can take four steps when in possession of the ball after which they can either bounce the ball off the ground or use the solo technique which involves kicking the ball from foot to hand (21). Possession can also be maintained by passing the ball using either the foot or the hand (3). Possession can be regained by dispossessing an opposing player or catching a pass, free or kick-out played by the opposing team.

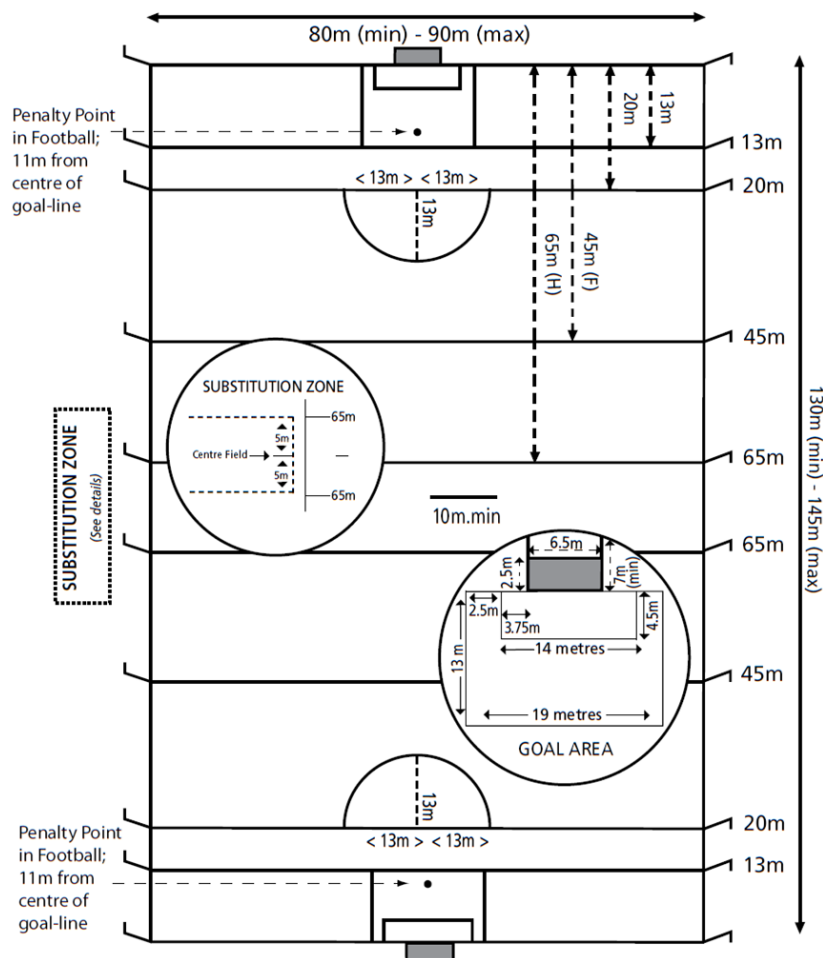


Figure 2.1. Dimensions of the playing field, goal area and substitution zone in Gaelic football.

Team formations have traditionally involved a goalkeeper, two defensive lines, a midfield duo, and two forward lines (3). The defensive and forward lines are further categorised into full-backs and half-backs and full-forwards and half-forwards, respectively with three players assigned to each line. The evolution of tactics has resulted in teams now deploying formations different to the traditional setup (22). At inter-county level, games consist of two 35 min periods with a short period of additional time (injury time) at the end of each half.

2.1.2 Competition structure

The NFL and the AIC are the two primary inter-county Gaelic football competitions organised annually. The NFL is organised in a divisional format based on ranking and commences in January. Each team plays 7 games with either 3 or 4 games played at a home venue. The top two teams in Divisions 2, 3, and 4 contest their respective league final to decide the division winners. The top four teams in Division 1 contest two semi-finals with the respective winner of each playing in the final. The league structure was reformatted for the 2021 season due to the Covid-19 pandemic, based on geographical location and rank consisting of four divisions of eight teams, with each division split into a north and south section.

The AIC is the premier inter-county competition and typically commences in April or May each year with teams participating on a knockout basis in four provincial championships (Connacht, Leinster, Munster, Ulster). The winners of each province progress directly into the AIS which involves eight teams. The losers of each successive round in the provincial championships enter the All-Ireland Qualifiers (AIQ), often referred

to as the 'back door' and can progress to the AIS by winning successive qualifying games. Between 2001 and 2017, the four provincial winners played the four winners of the qualifiers in a knockout format. In 2018 the GAA introduced the 'Super 8' format whereby the last remaining eight teams (four provincial winners and four qualifiers) compete in two groups of four teams in a round robin format with the top two teams in each group progressing to the semi-finals. In response to the Covid-19 pandemic, the 2020 and 2021 AIC was changed to a straight knockout format with the four provincial winners contesting the All-Ireland semi-finals.

2.1.3 Officiating

Games in Gaelic football are officiated by a referee with assistance from two linesmen and four goal-line umpires. The referee is required to keep up with play to be in the optimal position for decision making. The movement of the referee is unrestricted and dictated by the pattern of play. The linesmen signal when the ball goes out of play and indicate the direction of a line ball. Umpires, located at each of the four goal posts, are responsible for adjudicating the outcome when the ball crosses the end line. Linesmen and umpires do not signal for fouls during match play but can assist in decision making if requested by the referee and can bring fouls of various nature to the attention of the referee.

2.1.4 Types of foul play

Fouls in Gaelic football are classified as technical, aggressive and dissent. Technical fouls are often referred to as fouls relating to the ball such as running with the ball in hand for more than four steps, termed overcarrying, or any other foul that is not aggressive or

dissenting (23). Technical fouls are typically penalised by a free kick to the opposing team or the reversal of a free kick to a throw ball. Aggressive fouls involve the physical or verbal abuse of a player or official. Punishment for an aggressive foul can range from a free kick only to a dismissal and can carry long suspensions depending on the severity of the offence. Fouls relating to dissent can involve challenging the authority of the referee, failing to comply with the referee's instruction or showing dissent with the referee's decision. Punishment for dissent can also range from a free kick to a dismissal depending on the severity of the offence.

2.2 Motion analysis in invasion field-based team sports

Time motion analysis (TMA) involves the quantification of work rate and movement patterns (activity profile) in individual and team sports (6). An understanding of the activity profile of athletes during competition can help to facilitate the design of event-specific conditioning programmes (6). TMA systems have evolved considerably over the last four decades from manual video-based analysis systems (24) to more sophisticated automated computer-based tracking (CBT) systems and GPS technology (7, 25).

2.2.1 Manual video-based motion analysis

Since the late 1970's video-based motion analysis has been used to assess the activity profile of IFTS athletes during match play (24). This method involved placing a video recording device at a particular position of the playing field, usually at a height of ~15 m and distance of 30 – 40 m from the side-line, and tracking a single player throughout the entirety of a game (26). Player movements were broken down into a number of velocity-based movement categories ranging from walking to maximal effort. The distance covered during each discrete movement was determined as the product of the mean velocity and duration of each movement period. Total distance can subsequently be calculated as the sum of the distance covered within each movement category (26). Although pioneering, manual video-based motion analysis is restricted to the analysis of one player at a time, is both time and labour intensive and is susceptible to measurement error due to inter-observer differences (25, 27). Application of this methodology to the study of activity patterns of athletes participating in IFTS is therefore limited.

2.2.2 Computer-based tracking systems

Developments in computer software and hardware, and improvements in the resolution of recording devices has advanced early manual video-based analysis methods to semi-automated CBT systems. These systems overcome some of the limitations associated with manual analysis methods such as reduced processing time, greater objectivity, improved validity and reliability, and the provision of real-time data (25). However, these methods are far more costly, with some capable of only single player analysis (25).

A number of commercially available systems are capable of tracking multiple players during match play e.g., Prozone, AMISCO Pro, TRACAB. These systems require the installation of several permanent cameras at specific, elevated locations around a stadium to ensure the entire playing surface is in view at all times (28). The dimensions of the playing surface and precise camera locations are then used to transform the playing surface into a 2D model. Player movement can therefore be tracked using location data (x, y coordinates) with mathematical modelling, image processing techniques and automated computer programs that quantify a number of movement variables such as the total distance covered and distance covered within a number of velocity-based movement categories (25). Operators are required to further ensure that players are tracked correctly and amend any erroneous data (28). Although these systems have demonstrated good levels of validity (0.4% CV) and good-moderate levels of reliability (2 – 7% CV) for measurements of speed and distance (28, 29), and provide the advantage of not requiring players to wear additional equipment, their associated high costs, the fixed positioning of

the systems within stadia, and the requirement for a number of trained personnel limits their use to primarily elite professional IFTS.

2.2.3 Global positioning system technology

GPS technology, a satellite-based navigational system initially developed for military use, is widely used in daily civilian life through devices such as laptops and mobile phones for navigation purposes and in the land transportation, aviation and maritime industries for vehicle tracking (30). GPS technology involves the use of 24 orbiting satellites equipped with an atomic clock that when connected to a GPS receiver on earth, transmit information on their exact time (ephemeris) (30). The distance of a satellite to the GPS receiver is the product of the signal travel time and the speed of light (31). Provided the GPS receiver is connected to a minimum of four satellites, the precise location of the receiver on earth and its altitude can subsequently be determined trigonometrically (31). Both distance covered and velocity of movement are calculated using positional differentiation (latitude and longitude) or Doppler shift. Doppler shift is the most common method used by commercial GPS developers to calculate velocity by measuring the change in frequency of the signal from the receiver (32).

Modern GPS units are lightweight, portable and robust making them ideally suited for use with athletes participating in dynamic IFTS. They provide large quantities of data on the movement velocities and distances covered by athletes during training and competition (5, 6). Training and game-based GPS data have been used to optimise training programs, monitor training load, mitigate the risk of injury and identify key performance indicators (5, 6, 33). Sampling rate, the frequency at which GPS units collect movement

information (34), has increased considerably from early models that sampled at a rate of 1 Hz. Commercial GPS units sampling between 5 Hz and 18 Hz are now available and provide more valid and reliable data on speed and distance than earlier models (5, 35). Some GPS units are now capable of accessing the global navigation satellite system (GNSS), an umbrella term used to describe all the satellite navigation systems globally (GPS, GLONASS, Galileo, BeiDou). GNSS enhances measurement accuracy compared to GPS only (32, 36).

2.2.4 Validity and reliability of GPS and GNSS technology

Validity and reliability are essential components of any test or measurement device. Validity refers to the accuracy of a test to measure what it is intending to measure. Evaluating the validity of a measuring device involves comparison with a criterion or 'gold standard' measure (criterion validity). Statistical measures used to describe validity include bias, standard error of estimate (SEE), standard error of measurement (SEM), technical error of measurement (TEM) and the coefficient of variation (CV) (5, 37). Reliability refers to the consistency or repeatability of a test or measurement device in its measurement accuracy. Both inter and intra-unit reliability of GPS and GNSS units are important considering that comparisons are routinely undertaken between athletes and between exercise sessions. Statistical measures used to describe reliability include TEM, CV and intraclass correlation coefficient (ICC) (38). Values of <5%, 5 – 10% and >10% for the TEM or CV are often used to classify reliability as good, moderate or poor, respectively (5, 39). It is important that these thresholds are considered within the context of the measurement device being used as the values are arbitrary, and may in some cases lack

the necessary levels of sensitivity to detect meaningful change (38). These reference values have also been used in studies examining the validity of GPS and GNSS units although no consensus on the optimal classifications for validity are currently available (5).

There is currently no gold standard protocol to examine validity and reliability of GPS and GNSS technology. A range of testing batteries, involving linear and non-linear courses of varying distances and intensities, have been reported in the scientific literature. These studies have used a variety of criterion measures for speed and distance such as infrared timing gates, radar speed gun, measuring tape, and calibrated trundle wheel (5). These methodological differences should be considered when comparing and contrasting results between models.

2.2.4.1 Validity and reliability of 1 – 5 Hz GPS units

The first study to examine the validity of GPS technology for the measurement of physical activity involved a single participant who wore a GPS receiver sampling at a rate of 1 Hz, while undertaking bouts of steady state walking and running at velocities ranging from 2 – 20 km·h⁻¹ (40). The velocities measured with the GPS receiver were highly correlated ($r = 0.99$) with a certified chronometer (40). Subsequently, commercial GPS units sampling at 1 Hz have demonstrated acceptable levels of validity and reliability when measuring total distance and peak running speed (27, 41). However, high levels of measurement error and poor intra and inter-unit reliability have been reported while performing at a range of movement intensities on both linear and non-linear courses. In particular, the levels of measurement error increase during the high and very high-intensity movements that are characteristic of IFTS (5).

Similar to 1 Hz GPS units, 5 Hz units have acceptable levels of validity and reliability when measuring total distance and peak running speed (34, 42). However, they do not consistently achieve acceptable levels of validity and intra or inter-unit reliability during linear and non-linear movements at a range of intensities. Measurement accuracy and intra-unit reliability of 5 Hz GPS units was found to be suboptimal among athletes when jogging, striding and sprinting in a straight line over 40 m (43). Inter-unit reliability for HSR (18 – 25 km·h⁻¹) was found to be poor (10.8% TEM) and worsened considerably (112% TEM) when sprinting (>25 km·h⁻¹) while undertaking a specially designed team sport circuit (34). The large measurement error and poor reliability of 1 Hz and 5 Hz GPS units limits their suitability for use during intermittent IFTS. A summary of the validity and reliability of 1 Hz and 5 Hz GPS units is presented in Table 2.1 – 2.2 and Table 2.3 – 2.4, respectively.

Table 2.1. Summary of the validity of 1 Hz GPS technology

Unit	Criterion	Movement/Protocol	Measurement	Validity	Reference	
SPI-10	Trundle wheel	Running circuit (128 – 1386 m)	Total distance	Bias = 4.8%	Edgecomb and Norton, 2006 (27)	
SPI-10	Measuring tape	Team sport circuit (128.5 m)	Total distance	Bias = -4.1%	Coutts and Duffield, 2010 (41)	
	Timing gates	Linear sprint (20 m)	Peak speed	r = -0.40 – -0.53		
SPI Elite	Measuring tape	Team sport circuit (128.5 m)	Total distance	Bias = -2.0%		
	Timing gates	Linear sprint (20 m)	Peak speed	r = -0.40 – -0.53		
WiSPI	Measuring tape	Team sport circuit (128.5 m)	Total distance	Bias = 0.7%		
	Timing gates	Linear sprint (20 m)	Peak speed	r = -0.40 – -0.53		
MinimaxX	Timing gates	Straight line run (10 m, 20 m, 40 m and 20 – 40 m)	Walking	SEE = 9.6 – 23.8%	Jennings et al., 2010 (43)	
			Jogging	SEE = 11.5 – 25.7%		
			Striding	SEE = 11.3 – 31.1%		
			Sprinting	SEE = 12.2 – 32.4%		
		Tight change of direction (40 m)	Walking	SEE = 12.6%		
			Jogging	SEE = 9.0%		
			Striding	SEE = 10.4%		
			Sprinting	SEE = 12.5%		
		Gradual change of direction (40 m)	Walking	SEE = 9.1%		
			Jogging	SEE = 10.2%		
			Striding	SEE = 11.5%		
			Sprinting	SEE = 12.7%		
		Measuring tape	Team sport circuit (140 m)	Total distance		SEE = 3.6%

Table 2.1 (continued). Summary of the validity of 1 Hz GPS technology

Unit	Criterion	Movement/Protocol	Measurement	Validity	Reference
MinimaxX	Trundle wheel	Linear course (51 m)	Walking distance (1.79 m·s ⁻¹)	SEE = 2.7%	Portas et al., 2010 (42)
			Running distance (3.58 m·s ⁻¹)	SEE = 2.6%	
		Multidirectional course (37.5 – 180 m)	Walking distance (1.79 m·s ⁻¹)	SEE = 1.8 – 4.2%	
			Running distance (3.58 m·s ⁻¹)	SEE = 2.4 – 6.8%	
		Soccer-specific course (121 – 197 m)	Total distance	SEE = 1.3 – 3.0%	

SEE, standard error of estimate; r, correlation coefficient.

Table 2.2. Summary of the validity of 5 Hz GPS technology

Unit	Criterion	Movement/Protocol	Measurement	Validity	Reference
MinimaxX	Timing gates	Straight line run (10 m, 20 m, 40 m and 20 – 40 m)	Walking	SEE = 9.8 – 21.3%	Jennings et al., 2010 (43)
			Jogging	SEE = 10.7 – 23.2%	
			Striding	SEE = 9.0 – 27.4%	
			Sprinting	SEE = 11.9 – 30.9%	
		Tight change of direction (40 m)	Walking	SEE = 9.9%	
			Jogging	SEE = 10.6%	
			Striding	SEE = 10.8%	
			Sprinting	SEE = 11.5%	
		Gradual change of direction (40 m)	Walking	SEE = 8.9%	
			Jogging	SEE = 9.7%	
			Striding	SEE = 11.0%	
			Sprinting	SEE = 11.7%	
MinimaxX	Measuring tape	Team sport circuit (140 m)	Total distance	SEE = 3.8%	Portas et al., 2010 (42)
	Trundle wheel	Linear course (51 m)	Walking distance (1.79 m·s ⁻¹)	SEE = 3.1%	
Running distance (3.58 m·s ⁻¹)			SEE = 2.9%		
Multidirectional course (37.5 – 180 m)		Walking distance (1.79 m·s ⁻¹)	SEE = 2.2 – 4.4%		
		Running distance (3.58 m·s ⁻¹)	SEE = 2.2 – 3.6%		
		Soccer-specific course (121 – 197 m)	Total distance	SEE = 1.5 – 2.2%	

Table 2.2 (continued). Summary of the validity of 5 Hz GPS technology

Unit	Criterion	Movement/Protocol	Measurement	Validity	Reference
MinimaxX	Measuring tape	Team sport circuit (130.5 m)	Total distance	No significant difference	Johnston et al., 2012 (34)
	Timing gates	Linear sprint (50 m)	Average speed	No significant difference	
			Total distance	No significant difference	
	Radar speed gun		Peak speed	No significant difference	
MinimaxX v2.0	Tripod-mounted laser	Straight line running	Constant velocity (1 – 3 m·s ⁻¹)	CV = 11.1%	Varley et al., 2012 (44)
			Constant velocity (3 – 5 m·s ⁻¹)	CV = 10.6%	
			Constant velocity (5 – 8 m·s ⁻¹)	CV = 3.6%	
			Acceleration (1 – 3 m·s ⁻¹)	CV = 14.9%	
			Acceleration (3 – 5 m·s ⁻¹)	CV = 9.5%	
			Acceleration (5 – 8 m·s ⁻¹)	CV = 7.1%	
			Deceleration (5 – 8 m·s ⁻¹)	CV = 33.2%	

CV, coefficient of variation; SEE, standard error of estimate.

Table 2.3. Summary of the reliability of 1 Hz GPS technology

Unit	Type	Movement/Protocol	Measurement	Reliability	Reference
SPI-10	Intra	Running circuit (128 – 1386 m)	Total distance	TEM = 5.5%	Edgecomb and Norton 2006, (27)
SPI-10	Intra	Team sport circuit (128.5 m)	Total distance	CV = 4.5%	Coutts and Duffield, 2010 (41)
			Lap distance	CV = 6.4%	
			Low-intensity activity (<14.4 km·h ⁻¹)	CV = 5.3%	
			High-intensity running (>14.4 km·h ⁻¹)	CV = 32.4%	
			Very-high intensity running (>20.0 km·h ⁻¹)	CV = 30.4%	
		Linear sprint (20 m)	Peak speed	CV = 5.8%	
SPI Elite	Intra	Team sport circuit (128.5 m)	Total distance	CV = 3.6%	
			Lap distance	CV = 4.0%	
			Low-intensity activity (<14.4 km·h ⁻¹)	CV = 4.3%	
			High-intensity running (>14.4 km·h ⁻¹)	CV = 11.2%	
			Very-high intensity running (>20.0 km·h ⁻¹)	CV = 15.4%	
		Linear sprint (20 m)	Peak speed	CV = 2.3%	

Table 2.3 (continued). Summary of the reliability of 1 Hz GPS technology

Unit	Type	Movement/Protocol	Measurement	Reliability	Reference
WiSPI	Intra	Team sport circuit (128.5 m)	Total distance	CV = 7.1%	Coutts and Duffield, 2010 (41)
			Lap distance	CV = 7.2%	
			Low-intensity activity (<14.4 km·h ⁻¹)	CV = 12.5%	
			High-intensity running (>14.4 km·h ⁻¹)	CV = 20.4%	
MinimaxX	Inter	Linear sprint (20 m)	Very-high intensity running (>20.0 km·h ⁻¹)	CV = 11.5%	Jennings et al., 2010 (43)
			Peak speed	CV = 4.9%	
		Straight line run (10 m, 20 m, 40 m and 20 – 40 m)	Walking	CV = 7.0 – 30.8%	
			Jogging	CV = 9.4 – 34.7%	
			Striding	CV = 10.5 – 58.8%	
			Sprinting	CV = 11.5 – 77.2%	
		Tight change of direction (40 m)	Walking	CV = 17.5%	
			Jogging	CV = 8.6%	
			Striding	CV = 10.8%	
			Sprinting	CV = 12.0%	
		Gradual change of direction (40 m)	Walking	CV = 11.6%	
			Jogging	CV = 9.0%	
			Striding	CV = 12.2%	
			Sprinting	CV = 14.0%	
Team sport circuit (140 m)	Total distance	CV = 3.6%			

Table 2.3 (continued). Summary of the reliability of 1 Hz GPS technology

Unit	Type	Movement/Protocol	Measurement	Reliability	Reference
MinimaxX	Intra	Linear course (51 m)	Walking distance (1.79 m·s ⁻¹)	CV = 4.4%	Portas et al., 2010 (42)
			Running distance (3.58 m·s ⁻¹)	CV = 4.5%	
		Multidirectional course (37.5 – 180 m)	Walking distance (1.79 m·s ⁻¹)	CV = 3.1 – 5.7%	
			Running distance (3.58 m·s ⁻¹)	CV = 4.1 – 7.7%	
		Soccer-specific course (121 – 197 m)	Total distance	CV = 2.0 – 4.9%	

CV, coefficient of variation; TEM, technical error of measurement.

Table 2.4. Summary of the reliability of 5 Hz GPS technology

Unit	Type	Movement/Protocol	Measurement	Reliability	Reference			
MinimaxX	Inter	Straight line run (10 m, 20 m, 40 m and 20 – 40 m)	Walking	CV = 6.6 – 23.3%	Jennings et al., 2010 (43)			
			Jogging	CV = 9.1 – 22.8%				
			Striding	CV = 8.0 – 33.4%				
			Sprinting	CV = 9.2 – 39.5%				
		Tight change of direction (40 m)	Walking	CV = 15.2%				
			Jogging	CV = 8.6%				
			Striding	CV = 9.7%				
			Sprinting	CV = 9.2%				
		Gradual change of direction (40 m)	Walking	CV = 11.5%				
			Jogging	CV = 10.0%				
			Striding	CV = 9.9%				
			Sprinting	CV = 7.9%				
		MinimaxX	Intra	Team sport circuit (140 m)		Total distance	CV = 3.6%	Portas et al., 2010 (42)
				Linear course (51 m)		Walking distance (1.79 m·s ⁻¹)	CV = 5.3%	
						Running distance (3.58 m·s ⁻¹)	CV = 4.6%	
				Multidirectional course (37.5 – 180 m)		Walking distance (1.79 m·s ⁻¹)	CV = 3.4 – 6.7%	
Running distance (3.58 m·s ⁻¹)	CV = 3.7 – 6.1%							
Soccer-specific course (121 – 197 m)	Total distance			CV = 2.2 – 4.5%				

Table 2.4 (continued). Summary of the reliability of 5 Hz GPS technology

Unit	Type	Movement/Protocol	Measurement	Reliability	Reference	
MinimaxX	Inter	Team sport circuit (130.5 m)	Total distance	TEM = 2.0%	Johnston et al., 2012 (34)	
			Walking distance ($<6.0 \text{ km}\cdot\text{h}^{-1}$)	TEM = 7.5%		
			Jogging distance ($6.0 - 12.0 \text{ km}\cdot\text{h}^{-1}$)	TEM = 8.2%		
			Running distance ($12.0 - 18.0 \text{ km}\cdot\text{h}^{-1}$)	TEM = 5.6%		
			High-speed running distance ($18.0 - 25.0 \text{ km}\cdot\text{h}^{-1}$)	TEM = 10.8%		
			Sprinting distance ($>25.0 \text{ km}\cdot\text{h}^{-1}$)	TEM = 112.0%		
			Linear sprint (50 m)	Average speed		TEM = 7.5%
				Very-high intensity distance ($>20.0 \text{ km}\cdot\text{h}^{-1}$)		TEM = 59.3%
				Sprinting distance ($>25.0 \text{ km}\cdot\text{h}^{-1}$)		TEM = 20.1%
			Peak speed	CV = 9.2%		

Table 2.4 (continued). Summary of the reliability of 5 Hz GPS technology

Unit	Type	Movement/Protocol	Measurement	Reliability	Reference
MinimaxX v2.0	Inter	Straight line running	Constant velocity (1 – 3 m·s ⁻¹)	CV = 12.4%	Varley et al., 2012 (44)
			Constant velocity (3 – 5 m·s ⁻¹)	CV = 6.7%	
			Constant velocity (5 – 8 m·s ⁻¹)	CV = 6.3%	
			Acceleration (1 – 3 m·s ⁻¹)	CV = 16.2%	
			Acceleration (3 – 5 m·s ⁻¹)	CV = 9.5%	
			Acceleration (5 – 8 m·s ⁻¹)	CV = 11.0%	
			Deceleration (5 – 8 m·s ⁻¹)	CV = 31.8%	

CV, coefficient of variation; TEM, technical error of measurement.

2.2.4.2 Validity and reliability of ≥ 10 Hz GPS and GNSS units

GPS and GNSS units sampling at a rate of ≥ 10 Hz have repeatedly demonstrated positive improvements in validity and reliability for total distance and distance covered at a range of movement intensities compared to ≤ 5 Hz GPS units, particularly during short, high-intensity efforts which are common during intermittent IFTS (5, 44). Both 10 Hz GPS and 10 Hz GNSS units have high levels of measurement accuracy and good intra and inter-unit reliability for distance measured on a 400 m athletics track, 128.5 m pre-determined team sport circuit and a 20 m linear sprint. Similarly, both units have a high level of measurement accuracy and good intra and inter-unit reliability for peak speed, measured during a 20 m linear sprint (45–47).

Inter-unit reliability was reported to be good for total distance and distance covered at a range of movement intensities while performing a specially designed 40 min team sport simulation (48). During the 40 min simulation, large discrepancies were found in the inter-unit reliability of 10 Hz GPS and GNSS units for accelerations and decelerations between the software derived data and the raw data (48). Of note, the inter-unit reliability, expressed as a CV, during accelerations and decelerations for one of the 10 Hz GNSS units was 7 – 73% and 3 – 12% for the software-derived data and raw data, respectively. These differences highlight the effect of pre-processing filtering algorithms on activity data and the lack of clarity on this process provided by the manufacturers. The poor measure of reliability for both accelerations and decelerations calls into question the utility of these variables in the analysis of the activity profile of IFTS athletes.

To further capitalise on the enhanced measurement accuracy and reliability associated with increases in sampling rate, 15 Hz and 18 Hz GPS units are now available. A comparative analysis between 10 Hz and 15 Hz GPS units found that the 10 Hz units had a higher level of measurement accuracy for total distance and peak running speed during the performance of a 165 m team sport circuit, although both models were within 0.8 – 1.2% of the actual distance (49). Inter-unit reliability for total distance and peak running speed was also better when using the 10 Hz unit compared to the 15 Hz unit. A comparison of 18 Hz GPS and 10 Hz GNSS units found no significant difference between the two units for distance covered on a 400 m athletics track, a 128.5 m team sport circuit or 20 m trial with a difference in mean bias of <0.2% across all courses (45). A non-significant difference in peak running speed of 0.4% was also found between the 18 Hz GPS and 10 Hz GNSS units (45). In summary, increases in sampling rate beyond 10 Hz do not appear to provide further improvements in measurement accuracy or reliability. It should be noted that the 15 Hz and 18 Hz units used in previous studies have an initial sampling rate of 10 Hz which is supplemented through the in-built 100 Hz accelerometer. Such units may not accurately reflect the validity and reliability of units with a true sampling rate of 15 Hz and 18 Hz. A summary of the validity and reliability of ≥ 10 Hz GPS and GNSS units is presented in Table [2.5](#) and Table [2.6](#), respectively.

Table 2.5. Summary of the validity of 10 – 18 Hz GPS/GNSS technology

Unit	Criterion	Movement/Protocol	Measurement	Validity	Reference
MinimaxX v4.0 (10 Hz)	Measuring tape	Linear sprint (15 m)	Total distance	SEM = 3.8 – 9.6%	Castellano et al., 2011 (50)
		Linear sprint (30 m)	Total distance	SEM = 1.7 – 6.7%	
MinimaxX v4.0 (10 Hz)	Tripod-mounted laser	Straight line running	Constant velocity (1 – 3 m·s ⁻¹)	CV = 8.3%	Varley et al., 2012 (44)
			Constant velocity (3 – 5 m·s ⁻¹)	CV = 4.3%	
			Constant velocity (5 – 8 m·s ⁻¹)	CV = 3.1%	
			Acceleration (1 – 3 m·s ⁻¹)	CV = 5.9%	
			Acceleration (3 – 5 m·s ⁻¹)	CV = 4.9%	
			Acceleration (5 – 8 m·s ⁻¹)	CV = 3.6%	
			Deceleration (5 – 8 m·s ⁻¹)	CV = 11.3%	
			Total distance	No significant difference	
MinimaxX S4 (10 Hz)	Measuring tape	Team sport circuit (165 m)	Total distance	No significant difference	Johnston et al., 2014 (49)
			Timing gates	Peak speed	
SPI-ProX (15 Hz)	Measuring tape	Team sport circuit (165 m)	Total distance	No significant difference	
			Timing gates	Peak speed	
STATSports Viper (10 Hz)	Athletics track	Athletics track (400 m)	Total distance	Bias = 2.0%	Beato et al., 2018 (46)
	N/A	Team sport circuit (128.5 m)	Total distance	Bias = 2.7%	
		Linear course (20 m)	Total distance	Bias = 1.3%	
	Radar speed gun		Peak speed	Bias = 1.8%	

Table 2.5 (continued). Summary of the validity of 10 – 18 Hz GPS/GNSS technology

Unit	Criterion	Movement/Protocol	Measurement	Validity	Reference
STATSports Apex (10 Hz)	Athletics track	Athletics track (400 m)	Total distance	Bias = 1.1%	Beato et al., 2018 (45)
	N/A	Team sport circuit (128.5 m)	Total distance	Bias = 2.3%	
		Linear course (20 m)	Total distance	Bias = 1.1%	
		Radar speed gun		Peak speed	
STATSports (18 Hz)	Athletics track	Athletics track (400 m)	Total distance	Bias = 1.2%	
	N/A	Team sport circuit (128.5 m)	Total distance	Bias = 2.1%	
		Linear course (20 m)	Total distance	Bias = 1.2%	
		Radar speed gun		Peak speed	

CV, coefficient of variation; SEM, standard error of measurement.

Table 2.6. Summary of the reliability of 10 – 18 Hz GPS/GNSS technology

Unit	Type	Movement/Protocol	Measurement	Reliability	Reference
MinimaxX v4.0 (10 Hz)	Inter	Linear sprint (15 m)	Total distance	CV = 1.3%	Castellano et al., 2011 (50)
			Linear sprint (30 m)	Total distance	
MinimaxX v4.0 (10 Hz)	Inter	Straight line running	Constant velocity (1 – 3 m·s ⁻¹)	CV = 5.3%	Varley et al., 2012 (44)
			Constant velocity (3 – 5 m·s ⁻¹)	CV = 3.5%	
			Constant velocity (5 – 8 m·s ⁻¹)	CV = 2.0%	
			Acceleration (1 – 3 m·s ⁻¹)	CV = 4.3%	
			Acceleration (3 – 5 m·s ⁻¹)	CV = 4.2%	
			Acceleration (5 – 8 m·s ⁻¹)	CV = 1.9%	
			Deceleration (5 – 8 m·s ⁻¹)	CV = 6.0%	
			Total distance	TEM = 1.3%	
			Low-speed running distance (<14.0 km·h ⁻¹)	TEM = 1.7%	
			High-speed running distance (14.0 – 20.0 km·h ⁻¹)	TEM = 4.8%	
Very high-speed running distance (>20.0 km·h ⁻¹)	TEM = 11.5%				
Peak speed	TEM = 1.6%				
MinimaxX S4 (10 Hz)	Inter	Team sport circuit (165 m)	Total distance	TEM = 1.3%	Johnston et al., 2014 (49)
			Low-speed running distance (<14.0 km·h ⁻¹)	TEM = 1.7%	
			High-speed running distance (14.0 – 20.0 km·h ⁻¹)	TEM = 4.8%	
			Very high-speed running distance (>20.0 km·h ⁻¹)	TEM = 11.5%	
			Peak speed	TEM = 1.6%	

Table 2.6 (continued). Summary of the reliability of 10 – 18 Hz GPS/GNSS technology

Unit	Type	Movement/Protocol	Measurement	Reliability	Reference
SPI-ProX (15 Hz)	Inter	Team sport circuit (165 m)	Total distance	TEM = 1.9%	Johnston et al., 2014 (49)
			Low-speed running distance (<14.0 km·h ⁻¹)	TEM = 2.0%	
			High-speed running distance (14.0 – 20.0 km·h ⁻¹)	TEM = 7.6%	
			Very high-speed running distance (>20.0 km·h ⁻¹)	TEM = 12.1%	
			Peak speed	TEM = 8.1%	
STATSports Viper (10 Hz)	Intra	Athletics track (400 m)	Total distance	CV = 1.6%	Beato et al., 2018 (46)
		Team sport circuit (128.5 m)	Total distance	CV = 0.8%	
		Linear course (20 m)	Total distance	CV = 0.4%	
STATSports Viper (10 Hz)	Inter	Linear sprint	Peak speed (5 – 10 m)	CV = 0.7%	Beato and de Keijzer, 2019 (47)
			Peak speed (10 – 15 m)	CV = 4.9%	
			Peak speed (15 – 20 m)	CV = 4.4%	
			Peak speed (20 – 30 m)	CV = 3.1%	
			Peak speed (5 – 30 m)	CV = 2.6%	
			Peak speed (5 – 30 m)	CV = 3.3%	

Table 2.6 (continued). Summary of the reliability of 10 – 18 Hz GPS/GNSS technology

Unit	Type	Movement/Protocol	Measurement	Reliability	Reference
STATSports Apex (10 Hz)	Inter	Linear sprint	Peak speed (5 – 10 m)	CV = 2.9%	Beato and de Keijzer, 2019 (47)
			Peak speed (10 – 15 m)	CV = 2.2%	
			Peak speed (15 – 20 m)	CV = 2.0%	
			Peak speed (20 – 30 m)	CV = 1.6%	
			Peak speed (5 – 30 m)	CV = 1.9%	
STATSports Apex (10 Hz)	Inter	Team-sport circuit (software-derived)	Total distance	CV = 0.3%	Thornton et al., 2019 (48)
			Relative distance	CV = 0.3%	
			Peak speed	CV = 1.9%	
			Low-speed running (0 – 3 m·s ⁻¹)	CV = 0.7%	
			Moderate-speed running (3 – 5 m·s ⁻¹)	CV = 0.4%	
			High-speed running (>5 m·s ⁻¹)	CV = 1.3%	
			Accelerations (1 – 3 m·s ⁻²)	CV = 6.6 – 19.7%	
			Decelerations (-1 – -3 m·s ⁻²)	CV = 12.2 – 72.8%	

Table 2.6 (continued). Summary of the reliability of 10 – 18 Hz GPS/GNSS technology

Unit	Type	Movement/Protocol	Measurement	Reliability	Reference				
STATSports Apex (10 Hz)	Inter	Team-sport circuit (raw data)	Total distance	CV = 0.3%	Thornton et al., 2019 (48)				
			Relative distance	CV = 0.3%					
			Peak speed	CV = 1.9%					
			Low-speed running (0 – 3 m·s ⁻¹)	CV = 0.7%					
			Moderate-speed running (3 – 5 m·s ⁻¹)	CV = 0.4%					
			High-speed running (>5 m·s ⁻¹)	CV = 1.3%					
			Accelerations (1 – 3 m·s ⁻²)	CV = 3.1 – 4.9%					
			Decelerations (-1 – -3 m·s ⁻²)	CV = 4.6 – 11.9%					
			Catapult S5 (10 Hz)	Inter		Team-sport circuit (software-derived)	Total distance	CV = 1.5%	Thornton et al., 2019 (48)
							Relative distance	CV = 1.5%	
Peak speed	CV = 0.3%								
Low-speed running (0 – 3 m·s ⁻¹)	CV = 5.5%								
Moderate-speed running (3 – 5 m·s ⁻¹)	CV = 0.6%								
High-speed running (>5 m·s ⁻¹)	CV = 1.0%								
Accelerations (1 – 3 m·s ⁻²)	CV = 2.1 – 3.4%								
Decelerations (-1 – -3 m·s ⁻²)	CV = 4.4 – 12.8%								

Table 2.6 (continued). Summary of the reliability of 10 – 18 Hz GPS/GNSS technology

Unit	Type	Movement/Protocol	Measurement	Reliability	Reference				
Catapult S5 (10 Hz)	Inter	Team-sport circuit (raw data)	Total distance	CV = 0.9%	Thornton et al., 2019 (48)				
			Relative distance	CV = 0.9%					
			Peak speed	CV = 0.3%					
			Low-speed running (0 – 3 m·s ⁻¹)	CV = 4.4%					
			Moderate-speed running (3 – 5 m·s ⁻¹)	CV = 0.3%					
			High-speed running (>5 m·s ⁻¹)	CV = 0.8%					
			Accelerations (1 – 3 m·s ⁻²)	CV = 2.3 – 5.9%					
			Decelerations (-1 – -3 m·s ⁻²)	CV = 1.7 – 4.1%					
			GPSports EVO (10 Hz)	Inter		Team-sport circuit (software-derived)	Total distance	CV = 0.2%	Thornton et al., 2019 (48)
							Relative distance	CV = 0.2%	
Peak speed	CV = 0.2%								
Low-speed running (0 – 3 m·s ⁻¹)	CV = 0.8%								
Moderate-speed running (3 – 5 m·s ⁻¹)	CV = 0.4%								
High-speed running (>5 m·s ⁻¹)	CV = 0.5%								
Accelerations (1 – 3 m·s ⁻²)	CV = 1.4 – 4.2%								
Decelerations (-1 – -3 m·s ⁻²)	CV = 2.5 – 10.9%								

Table 2.6 (continued). Summary of the reliability of 10 – 18 Hz GPS/GNSS technology

Unit	Type	Movement/Protocol	Measurement	Reliability	Reference
GPSports EVO (10 Hz)	Inter	Team-sport circuit (raw data)	Total distance	CV = 0.2%	Thornton et al., 2019 (48)
			Relative distance	CV = 0.2%	
			Peak speed	CV = 0.2%	
			Low-speed running (0 – 3 m·s ⁻¹)	CV = 0.4%	
			Moderate-speed running (3 – 5 m·s ⁻¹)	CV = 0.4%	
			High-speed running (>5 m·s ⁻¹)	CV = 0.5%	
			Accelerations (1 – 3 m·s ⁻²)	CV = 2.6 – 5.6%	
			Decelerations (-1 – -3 m·s ⁻²)	CV = 1.8 – 7.8%	

CV, coefficient of variation; TEM, technical error of measurement.

2.2.5 GPS and GNSS data processing and reporting standards

In addition to sampling rate, the validity and reliability of GPS and GNSS units are influenced by the signal quality. Signal quality of GPS and GNSS units can be evaluated through examination of the number of satellites connected to the unit and their dispersion around the globe (32). An increase in the number of satellites connected to a GPS or GNSS unit will likely enhance the signal quality (36). Units connected to <6 satellites are reported to have weaker signal quality and subsequently poorer validity and reliability (32). In contrast, units capable of accessing the GNSS network may have greater signal quality, making them more sensitive to deviations in speed and positioning than GPS only units (32, 36).

The dispersion of the satellites relative to one another is known as the horizontal dilution of precision (HDOP). The HDOP is measured on a scale ranging from 0 – 50 with values close to zero considered optimal and values closer to 50 deemed unreliable (32, 51). Ideal positioning of the satellites involves one directly overhead and the rest evenly spaced across the horizon (51). When satellites are clustered tightly together, directly overhead, the HDOP is high and the signal quality is poor (51). In a comparative study between GPS and GNSS units, the HDOP was 25% lower for the GNSS units than the GPS units during a team sport circuit involving a range of movement intensities, likely representative of a greater precision of measurement for GNSS units (36). Differences in the distance covered at a range of intensities, and during accelerations and decelerations were also found between the GNSS and GPS units during the team sport circuit and match play.

Most modern GPS and GNSS user software provide information on the number of satellites connected to the units and the HDOP at a given time point which was not available with earlier models (32, 46). Access to this information provides an additional level of scrutiny in relation to the assessment of the validity and reliability of activity data. At present, there is no standardised criteria on the acceptable number of connected satellites or HDOP values. Recent studies have proposed the use of cut-off points to improve data quality and reporting accuracy for the number of satellites connected and the HDOP (32). For example, in studies examining the activity profile of IFTS, where the number of satellites connected to the unit was <8 (52), or the HDOP >2.0 (52, 53), data points were excluded from further analysis. At a minimum, the average number of satellites connected to the GPS or GNSS unit, the HDOP value, and information regarding the software and firmware should be reported (32).

2.3 Velocity-based movement categories

The distance covered by players and referees in a number of velocity-based movement categories is one of the most commonly reported activity profile variables in soccer, rugby league, rugby union, Australian football and Gaelic football (7, 13, 54). These categories vary in intensity and are associated with verbal descriptors such as low, moderate or high-speed. Velocity-based movement categories were initially used during the early TMA studies to gain a greater insight into the total distance covered by players and referees during intermittent IFTS (14, 55). This information has subsequently been used to develop training programs that replicate the activity profile during match play (6).

Despite this approach being used extensively, no consensus exists on the most appropriate number of movement categories or their associated velocity thresholds. The velocity thresholds used in the majority of studies involving CBT or GPS/GNSS technology have been provided by the respective manufacturer. A major limitation to the adoption of manufacturer-based velocity thresholds is that they have been selected arbitrarily and lack a solid evidence base to support their use among athletes participating at all levels of IFTS (56, 57). The lack of reporting standards has resulted in a range of thresholds with practically identical verbal descriptors available in the scientific literature, both within and between sports. For example, within soccer alone, the velocity threshold used to denote HSR has ranged from 3.6 – 5.5 m·s⁻¹ (58–60). There is also considerable inconsistency around the verbal descriptors associated with different movement categories. In particular, the descriptor ‘intensity’ is commonly used alongside and interchangeably with

'speed' without evidence to support its efficacy in distinguishing between the exercise intensity domains (56, 61).

Exercise intensity for athletic populations is typically categorised into three distinct domains or 'zones' (61–63). Each domain, termed moderate, heavy and severe, displays a distinct blood lactate and oxygen uptake ($\dot{V}O_2$) response (Figure 2.2) (61–64). In the moderate domain, exercise can be maintained for prolonged periods of time (>4 hr). Blood lactate concentrations remain at baseline levels and $\dot{V}O_2$ rises at the onset of exercise before reaching a plateau or 'steady state'. As exercise transitions into the heavy domain, time to fatigue is reduced relative to the moderate domain. Blood lactate levels rise but reach a steady state, and $\dot{V}O_2$ demonstrates a delayed steady state response known as a slow component (65). Exercise in the severe domain is characterised by the absence of a steady state in both blood lactate concentration and $\dot{V}O_2$ (61, 66).

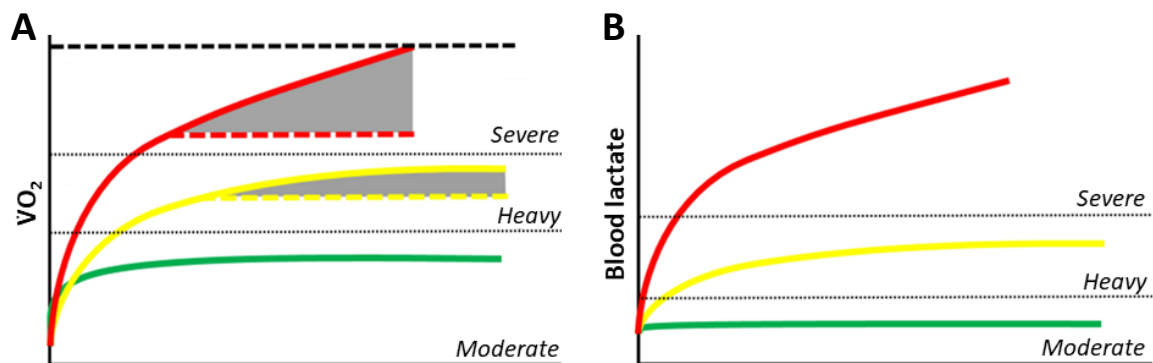


Figure 2.2. Representative example of the $\dot{V}O_2$ (A) and blood lactate (B) response during exercise at a constant work rate in each of the three exercise intensity domains. Adapted from Jamnick et al., 2020 (61).

The lactate threshold (LT), the first intensity at which blood lactate concentrations rise above baseline values (Figure 2.3A) (67), is regarded as the most appropriate method to demarcate the transition between the moderate and heavy intensity domains (66). In

combination with, or as a less invasive alternative to the LT, the gas exchange threshold (GET) is also commonly used to demarcate entry into the heavy intensity domain (61). The GET is based on the volume of expired gases independent of ventilation and is defined as the exercise intensity (metabolic rate) where carbon dioxide production ($\dot{V}CO_2$) can no longer attain a steady state. This results in excess $\dot{V}CO_2$ that is proportional to the rate at which bicarbonate in muscle and blood decrease, and is independent of hyperventilation (61, 63, 68). The GET can be identified through the examination of the relation between $\dot{V}CO_2$ and $\dot{V}O_2$ (V-slope method) (Figure 2.3B) or by plotting the excess in $\dot{V}CO_2$ against the $\dot{V}O_2$ during a laboratory-based incremental exercise test (61, 63). The GET is often interpreted interchangeably with the ventilatory threshold (VT), however they require independent determination (68). The VT involves analysing a quotient of minute ventilation ($\dot{V}E$) relative to $\dot{V}O_2$ ($\dot{V}E/\dot{V}O_2$) and $\dot{V}CO_2$ ($\dot{V}E/\dot{V}CO_2$), plotted against time, power output or $\dot{V}O_2$ (68). While the GET and VT represent relevant physiological responses during exercise (63), evidence to directly support their use in demarcating entry into the heavy intensity domain is limited (61).

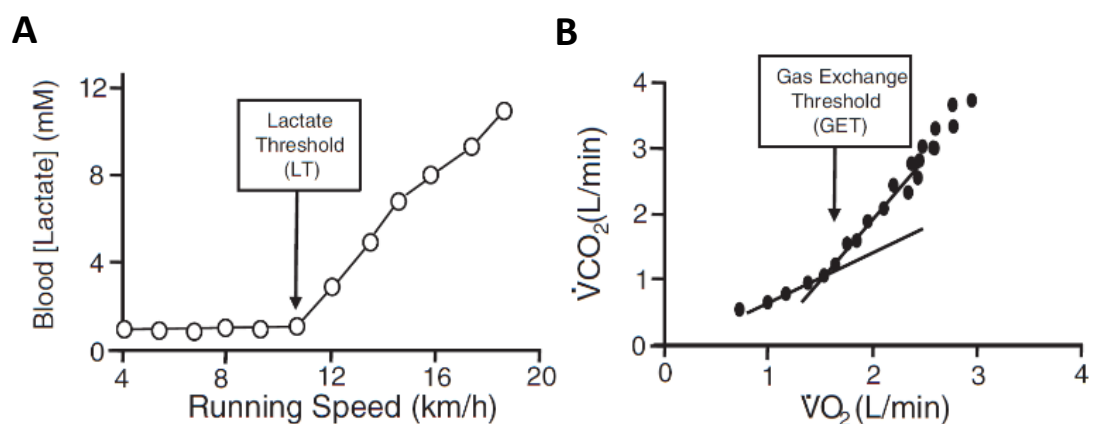


Figure 2.3. Representative example of the determination of the lactate threshold (A) and gas exchange threshold (V-slope method) (B) from an incremental exercise test. Adapted from Poole et al., 2021 (63).

Maximal lactate steady state (MLSS) and critical power (CP) are the two thresholds that best mark the transition between the heavy and severe exercise intensity domains (61–63, 66, 69). The MLSS is defined as the highest intensity of exercise that can be sustained without a continuous rise in blood lactate concentration (70, 71). The CP is defined as the highest intensity that can be maintained for a prolonged period with stable blood lactate and oxygen kinetics. Blood lactate concentrations and $\dot{V}O_2$ continue to rise at exercise intensities above CP (62, 63). Given the overlapping definitions of CP and MLSS, these terms have at times been used synonymously although discourse remains regarding the extent of their differences (62, 66, 72). The respiratory compensation point (RCP), sometimes referred to as the second ventilatory threshold (VT_2), has been proposed to demarcate the transition between the heavy and severe intensity domains. The RCP, caused by hyperventilation, is determined as the point at which $\dot{V}E$ increases without a concomitant increase in $\dot{V}CO_2$, resulting in a rise in $\dot{V}E/\dot{V}CO_2$ and a decrease in the partial pressure of carbon dioxide in arterial blood and end tidal carbon dioxide (73). Similar to the VT, evidence to directly support its use in demarcating entry into the severe domain is currently limited (61).

Although arbitrary velocity thresholds apply a uniform standard across intermittent IFTS, they fail to account for inter-individual differences in gender, age, biological maturation, and physical fitness levels. A one-size fits all approach to activity classification based on arbitrary velocity thresholds may therefore underestimate or overestimate the distance covered within each category. As an alternative, a number of studies have proposed the use of individual physiological thresholds and/or physical

performance indicators to identify transitions in exercise intensity domains and locomotor categories for athletes participating in IFTS (74–86).

2.3.1 Physiological thresholds

The first study to relativise movement category velocity thresholds using a physiological threshold anchored entry into a ‘high-intensity activity’ (HIA) category for elite soccer players on the speed at the RCP and compared the distance covered to a default HSR category of $>5.5 \text{ m}\cdot\text{s}^{-1}$ (75). For all players, the speed at the RCP was lower than the $>5.5 \text{ m}\cdot\text{s}^{-1}$ HSR threshold and resulted in a 167% (845 m vs 2258 m) difference between the two categories (75). In a follow up study, the speed at the VT and the RCP were used to demarcate the transition between low and moderate-intensity running and moderate and high-intensity running (HIR), respectively (82). Application of VT and the RCP to the activity data resulted in large differences in the distribution of the distances covered compared to the distance in a default HSR ($4.0 - 5.5 \text{ m}\cdot\text{s}^{-1}$) and very high-speed running (VHSR) ($\geq 5.5 \text{ m}\cdot\text{s}^{-1}$) category, respectively. In particular, the distance covered at a speed greater than the RCP was 165% higher than the distance covered at a speed $\geq 5.5 \text{ m}\cdot\text{s}^{-1}$. Interestingly, in the initial study using the RCP (75) HSR was defined as $>5.5 \text{ m}\cdot\text{s}^{-1}$. This speed was redefined as VHSR in the subsequent study by the same research group (82). Among women participating in Rugby Sevens there was a 30% increase in ‘HIR’ based on the RCP, compared to the default running speed of $5.0 \text{ m}\cdot\text{s}^{-1}$ (79).

Although the use of VT and RCP to relativise activity data was a novel attempt to objectively relativise movement category velocity thresholds, it requires trained personnel, access to expensive laboratory equipment and is susceptible to changes in

physical fitness requiring multiple testing sessions (87, 88). It is also unclear how the intermittent nature of IFTS and associated muscle/blood lactate and $\dot{V}O_2$ kinetics relate to physiological thresholds determined during laboratory-based incremental exercise (25, 61). The speed at a blood lactate concentration of 4.0 mM has been used to differentiate between exercise and recovery during match play in international rugby union players (89). Fixed blood lactate concentrations (FBLC) represent arbitrary metabolic intensities and are a poor discriminator of exercise intensity domains (61).

2.3.2 Physical performance indicators

As an alternative to the use of laboratory-based physiological thresholds, field-based physical performance indicators such as maximal sprint speed (MSS) and maximal aerobic speed (MAS) have been used to partition activity data (77, 78, 80, 81, 83, 84). The MSS approach has become popular due to its simplicity and relative ease to implement, and it is based on the highest value registered during training or match play (77, 81, 84). Unlike the LT, GET, MLSS or CP, MSS does not represent a particular intensity or threshold, it is simply the highest running speed that an individual can attain. This has led to a number of different 'cut points' based on MSS being reported in the literature. During IFTS, players and referees do not always achieve their MSS (90, 91). Consequently, caution should be taken when defining MSS using data collected during competition. In addition, GPS units with low sampling rates are susceptible to considerable measurement error during HSR efforts (5).

In rugby union, entry into a relative 'HSR' category was determined by dividing the mean MSS of the players by the default arbitrary HSR threshold of the particular GPS

manufacturer (84). This approach resulted in a difference of 18% and 32% for forwards and backs, respectively, in the distance covered at high-speed compared to the default category. Arbitrary MSS cut-points of 20%, 50%, 80%, 95% and 100% (77) and 25%, 50% and 70% in rugby (80), 30%, 50%, 60%, 75% and 95% in field hockey (78) and 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% and 90% in soccer (83) have also been reported, all without justification. The dearth of evidence to support any of these arbitrary values, or to demonstrate their superiority over traditional default velocity thresholds confounds the use of MSS in IFTS to partition activity data.

Some studies have recommended a more comprehensive approach to the discretisation of activity data based on a combination of physiological thresholds and physical performance indicators (81, 92). The first study to adopt a joint approach to the discretisation of activity data used both MSS and MAS (92). MAS was determined using a modified version of the Montreal Track Test (Vam-Eval test), a continuous, incremental running test controlled by audio signals that begins at $8 \text{ km}\cdot\text{h}^{-1}$ and increases by $0.5 \text{ km}\cdot\text{h}^{-1}$ every minute. The speed during the last successfully completed stage was defined as the MAS. The difference between the MSS and MAS was then calculated and termed the 'anaerobic speed reserve' (ASR) with five velocity thresholds subsequently proposed ($\leq 60\%$ MAS, $61 - 80\%$ MAS, $81 - 100\%$ MAS, 101% MAS $- 30\%$ ASR and $\geq 30\%$ ASR) (92).

More recently, four combinations of physiological and physical performance indicators were used to discretise activity data while a fifth approach used arbitrary velocity thresholds (81). The physiological thresholds used were i) RCP, determined during an incremental exercise test to volitional exhaustion on a treadmill, ii) MAS, defined as the

treadmill speed at test termination, iii) velocity at $\dot{V}O_{2max}$ ($v\dot{V}O_{2max}$), defined as the lowest speed which elicited a value $\geq 95\% \dot{V}O_{2max}$ and iv) MSS, defined as the fastest 10 m split during a 40 m linear sprint. For each method, four movement categories were generated, termed low-speed running (LSR), HSR, VHSR, and sprinting.

Using the RCP, $v\dot{V}O_{2max}$ and MSS, the first approach was labelled as the individualised approach (IND) with the movement category velocity thresholds defined as $<RCP$ (low speed running), $RCP - v\dot{V}O_{2max}$ (HSR), $v\dot{V}O_{2max} - 29\% ASR$ (VHSR) and $30\% ASR - MSS$ (sprinting). The second approach was termed MAS and separated into $<79\% MAS$ (LSR), $80 - 99\% MAS$ (HSR), $100 - 139\% MAS$ (VHSR) and $140\% MAS - 35 \text{ km}\cdot\text{h}^{-1}$ (sprinting). The third approach used MSS categories of $<49\% MSS$ (LSR), $50 - 59\% MSS$ (HSR), $60 - 79\% MSS$ (VHSR) and $80 - 100\% MSS$ (sprinting). The final approach involved MAS and MSS and was defined as LOCO, with categories separated into $<79\% MAS$ (LSR), $80 - 99\% MAS$ (HSR), $100\% MAS - 29\% ASR$ (VHSR) and $30\% ASR - MSS$ (sprinting).

When comparing the MSS approach to the IND approach in this same study, MSS misrepresented HSR and VHSR distance in 61% and 31% of cases, respectively. Similar differences were observed between the MAS and IND approaches, with the MAS approach misrepresenting HSR and VHSR distance in 50% and 28% of cases, respectively. Accordingly, it was concluded that MSS alone had limited utility beyond perhaps the classification of a 'sprinting' category and that an individualised approach, incorporating more than one physiological threshold and/or physical performance indicator reflective of the transitions in exercise intensity domains should be adopted (81). These studies however failed to address the aforementioned limitations regarding the requirement of

expensive laboratory equipment, and the use of arbitrary cut points to anchor the velocity thresholds. This makes it practically impossible to identify whether any of these approaches provide a greater insight into the demands of IFTS than traditional arbitrary categories. Failure to adequately address the limitations ultimately precludes the use of these approaches in the discretisation of activity data derived from IFTS players and referees.

2.3.3 Machine learning approach

Due to the limitations associated with the use of physiological thresholds and physical performance indicators, and the rapidly increasing sampling rates of micro-technology units, sophisticated data analytical methods are being used to analyse and relativise activity data (52, 93–95). Machine learning is a branch of computer science that can enhance the insights into large datasets using tools derived from mathematical and statistical disciplines, and has been applied within several elite sporting environments (96, 97).

Unsupervised clustering techniques are some of the most widely used machine learning techniques when undertaking multivariate data analysis (98). These methods organise data samples into distinct groups known as ‘clusters’ based on a certain similarity measure such as Euclidean distance (97). In a recent study, the *k*-means clustering approach was used to generate four movement category velocity thresholds for elite netball athletes (95). This approach randomly positions a pre-defined number of cluster centroids, *k*, into the dataset with each data point assigned to the nearest cluster centroid which is determined by its Euclidean distance (99). The position of the cluster centroids is

then recomputed to the average position of each associated data point. This process is repeated until no further movement of the cluster centroids take place. The values of the centroids were subsequently used as the velocity thresholds (95). The discretisation of activity data using this method is however limited in its application given the outcome of discretisation depends on the pre-defined k -value, the initial position of the chosen cluster centroids and the fact that each data point is treated independently making it sensitive to outliers (98).

Spectral clustering is a graph-based approach used to cluster multivariate data by dividing data points into groups such that data points in the same group are heavily connected and data points in different groups are not connected (100). This approach has become a popular method of clustering due to its ability to overcome some limitations of k -means (100). A spectral clustering technique applied to activity data of elite women's soccer players generated three unique velocity thresholds (52). These thresholds presented logical validity and resulted in differences of 18 – 61% and 6 – 93% in the distances covered at high and very high-speed, respectively, compared to thresholds derived from arbitrary movement categories and other machine learning techniques (Figure 2.4). The spectral clustering technique also permitted the generation of individual-specific categories with the player ranking similar for each boundary (52). Similarly, spectral clustering was used in elite youth female soccer to generate velocity thresholds, yielding a set of unique values for under-14, under-16 and youth (under-16 and under-14 combined) players that resulted in significant differences in the distance covered in each category between groups (94). Both the under-14 and under-16 thresholds were lower than those at senior level, with the under-14 thresholds also lower than under-16 (94).

Spectral clustering offers several advantages over the traditional arbitrary velocity thresholds and methods involving physiological thresholds or physical performance indicators. Firstly, this approach generates the velocity thresholds directly from the raw activity data. This removes the need for multiple dedicated laboratory or field-based testing sessions during the competitive season. As the thresholds generated from spectral clustering are calculated on a game to game basis they can be regularly updated. Secondly, the spectral clustering approach identifies the velocities which are traversed through the least, referred to as the minimum cut problem, likely reflecting the changes in locomotive categories and overcoming the limitation of arbitrary cut points. Finally, as the thresholds are generated separately for each player and each game, this approach permits the formation of both individual and group-based thresholds which is recommended, particularly in an applied setting (82).

Spectral clustering is not however without limitation. Consistent with the k -means approach, the number of clusters, k , need to be pre-defined. An increase or decrease in the number of clusters will alter the dispersion of the cluster centroids thereby changing the movement category velocity thresholds. Additionally, while significant differences have been observed in the dispersion of the total distance between spectral clustering, arbitrary movement categories and other machine learning approaches (52), no attempt has been made to examine the relation of these newly generated movement categories with the raw data. These areas need to be addressed in future studies applying a spectral clustering approach to activity data.

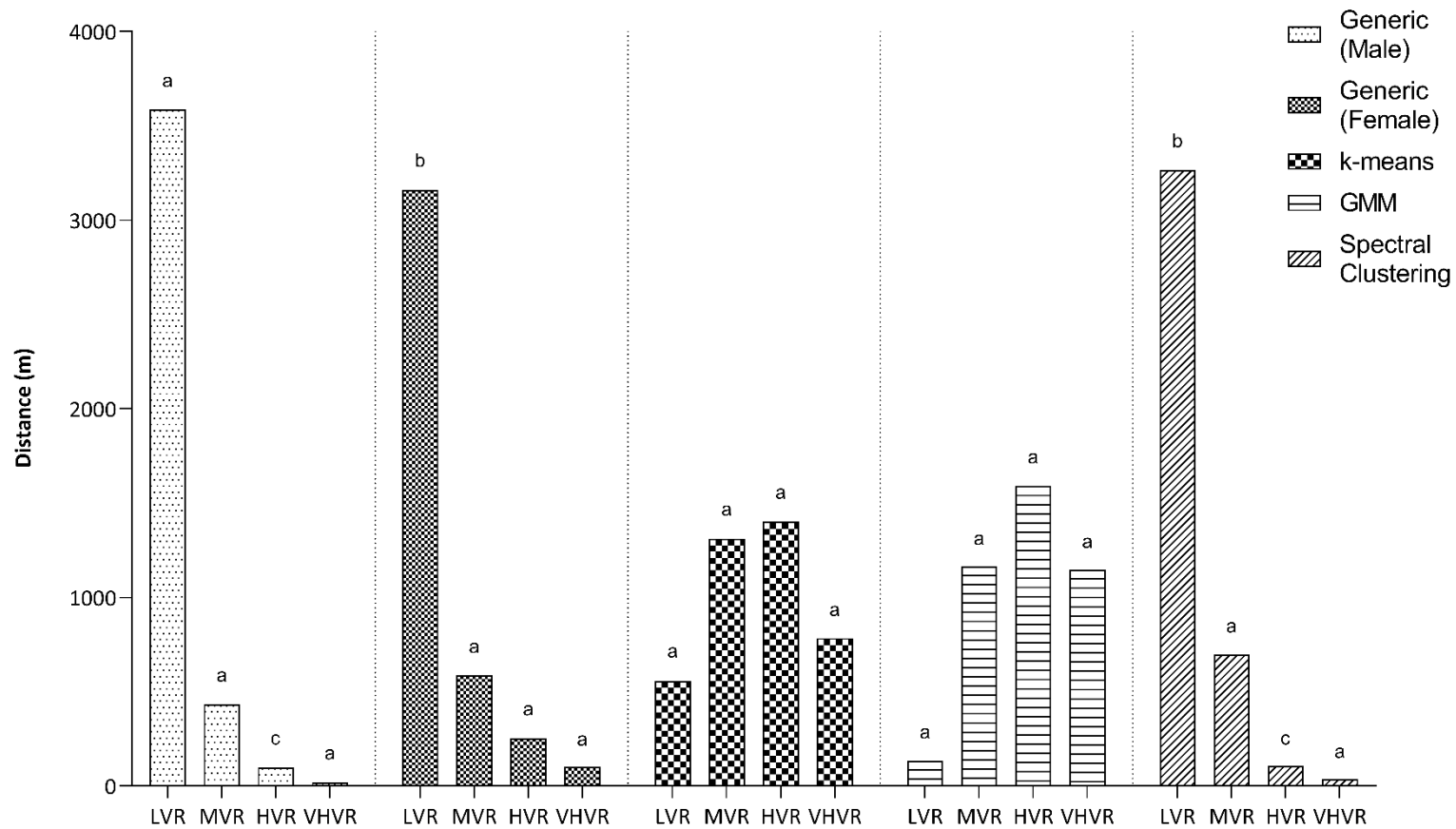


Figure 2.4. Distance covered in a range of movement categories for the analysis of elite women's soccer. GMM, Gaussian mixture model; LVR, low-velocity running; MVR, moderate-velocity running; HVR, high-velocity running; VHVR, very high-velocity running. Data are presented as mean. ^a different to all other methods; ^b different to Generic (Male), *k*-means, and GMM; ^c different to Generic (Female), *k*-means, and GMM. Adapted from Park et al., 2018 (52).

2.4 Match analysis of invasion field-based team sport referees

IFTS are very popular worldwide and are officiated by one or more referees. In Australian football and field hockey, umpires/referees are assigned to officiate a particular section of the playing area. In contrast, a single referee is primarily responsible for officiating IFTS such as soccer, rugby, and Gaelic football. The physical demands on referees are therefore likely to be much greater during soccer, rugby and Gaelic football compared to Australian football and field hockey. Although there is an increasing number of studies examining the activity profile of IFTS referees, research lags behind those involving players.

2.4.1 Soccer

Soccer is an intermittent IFTS governed by Fédération Internationale de Football Association (FIFA) and is the most popular sport played globally. Games are played between two teams of 11 players across two 45 min halves with each game officiated by a referee, two assistant referees and a fourth official. Soccer referees are required to keep up with play at all times, notwithstanding the relatively large playing area of ~100 m in length and ~64 m in width, and the intermittent nature of the sport. The assistant referees in soccer can signal the occurrence of foul play to the referee unrequested and are restricted to one half of the playing field (101, 102).

During elite competitions, soccer referees have been reported to make 104 – 162 observable decisions distributed evenly throughout a game (103). In addition, ~70 non-observable decisions are made that do not result in an interference with play (103). Soccer is a global industry that generates substantial revenue. Large financial implications are

dependent on the outcome of games, emphasising further the need for referees to be able to keep up with play at all times to ensure optimal positioning for decision making. Using a range of assessment methods, the activity profile and the physiological and metabolic responses of elite soccer referees during competitive games have been widely investigated (13).

2.4.1.1 Activity profile

Early research using manual video-based motion analysis found that elite soccer referees typically cover a total distance ranging from 9 to 11 km during match play. Most of this distance is covered at low and moderate speeds with ~10% at high-speed (14, 104, 105). Changes in movement intensity were reported to occur 1263 times, equating to once every 4.3 sec. An average of 161 HIR bouts were also reported, lasting on average 2.3 sec (14). These distances were comparable to those of elite players who cover ~11 km with the majority of the distance also covered at low and moderate speeds (26). More recent studies using CBT have found that elite referees cover an average distance of ~11.5 km with ~0.8 km of HIR ($>5.5 \text{ m}\cdot\text{s}^{-1}$) (60, 106). The use of different velocity thresholds makes it difficult to compare HIA across studies. In comparison to previous studies involving elite English referees published a decade earlier (104), the total distance covered is greater by ~18%. This increase may be due in part to enhanced preparation (14, 18), coupled with the professionalisation of elite referees in the English Premier league.

The short (8 week) and long (5 year) term variation in total distance covered by soccer referees and their peak running speed during match play is low (<6%) (107). Variation in the average distance of referees from play when awarding a foul is also low (8

– 10%) across both the short and long term. In contrast, the short and long-term variation in HSR ($>5.5 \text{ m}\cdot\text{s}^{-1}$) (22 – 25%) and the number of sprints (44 – 54%) is much higher (107). The large inter-game variability in HSR among referees may be partly explained by the large variability in HSR reported for elite players (108) given that a significant relation between mean HIR distance ($>5.5 \text{ m}\cdot\text{s}^{-1}$) undertaken by players and the referee has been reported (60, 106). The percentage difference in HIR distance of the referee and the players between the first and second half is also significantly correlated (106).

More recently, the activity profile of elite referees and players was examined in 5 min epochs across entire games (60). A significant, strong, positive correlation was found between the total ($r = 0.66$) and HSR ($r = 0.62$) distance ($>5.5 \text{ m}\cdot\text{s}^{-1}$) of the referee and players. Interestingly, the total distance was ~4% higher for the referee than the players despite the referees being 15 – 20 years older (60). A summary of the activity profile of elite soccer referees during match play is presented in Table [2.7](#).

2.4.1.2 Physiological responses

Assessment of HR is often used as an indirect measure of physiological strain during competition (21). Using the formula $220 - \text{age}$ to estimate maximal HR (HR_{max}), the mean HR of elite soccer referees was found to be 89 – 95% HR_{max} during competitive match play (104, 105). This equation however, underestimates HR_{max} in adults >40 years of age (109). When HR_{max} was determined using laboratory-based exercise testing or match play, lower values ranging from 82 – 85% HR_{max} were reported (14, 103, 110). Utilising the linear relation between HR and $\dot{V}\text{O}_2$ during incremental exercise (111), HR responses have been used to estimate the aerobic demand experienced by elite soccer referees during match

play. The estimated $\dot{V}O_2$ during competitive match play was reported to be 81% $\dot{V}O_{2max}$ (14). A major limitation of this approach is that the relation between HR and $\dot{V}O_2$ at very low and near maximal exercise intensities is not linear (111). In addition, the high-intensity efforts performed by elite IFTS referees are brief and may not be of adequate duration to observe the HR response.

To directly measure the oxygen kinetics of elite referees during competition, a cohort of elite Italian referees were fitted with a portable metabolic system (K2, Cosmed, Rome, Italy) during friendly games (112). Measures of oxygen consumption and HR were collected every 20 sec during the friendly games and relativised using laboratory-based $\dot{V}O_{2max}$ and HR_{max} . Referees were found to have a mean $\dot{V}O_2$ of 68% $\dot{V}O_{2max}$ with a mean HR of 89% HR_{max} . Given that the running performance was similar to previous studies involving referees, the results demonstrate the limitations associated with estimating $\dot{V}O_2$ using HR during match play.

Circulating levels of blood lactate were measured in elite referees to indirectly examine their metabolic responses during match play (14). Values of 4.8 (range: 2.0 – 9.8) mM and 5.1 (range: 2.3 – 14.0) mM have been reported at the end of the first and second half of competitive soccer games, respectively (14). High intra-individual variability was however observed (31% CV). In another study, blood lactate levels of the referee were 3.5, 7.3 and 3.4 mM at 15 min, 30 min and at half time, respectively during four friendly professional domestic soccer games (112). Measurements of blood lactate should however be interpreted with caution given the highly unpredictable nature of intermittent IFTS and the large variability in the physiological and metabolic responses.

Table 2.7. Summary of the activity profile of soccer referees during match play

Competition	Tracking Technology	Sample Size	Measurement	Value	Reference
English Football Leagues	Manual video-based motion analysis	Referees = 14 Games = 14	Total distance (m)	9,438 ± 707	Catterall et al., 1993 (104)
			Walking (m)	2,163 ± 527	
			Jogging (m)	4,444 ± 620	
			Sprinting (m)	1,109 ± 419	
			Reverse running (m)	1,722 ± 584	
Italian Serie A	Video-based motion analysis	Referees = 33 Games = 96	Total distance (m)	11,469 ± 983	D'Ottavio and Castagna, 2001 (105)
			Low-intensity running (m) (<13 km·h ⁻¹)	4,577 ± 561	
			Medium-intensity running (m) (13.1 – 18.0 km·h ⁻¹)	2,746 ± 535	
			High-intensity running (m) (18.1 – 24.0 km·h ⁻¹)	1,546 ± 419	
			Maximal speed running (m) (>24.0 km·h ⁻¹)	427 ± 308	
			Walking forward (m)	945 ± 161	
			Walking backward (m)	39 ± 22	
			Running backward (m)	867 ± 461	
			Running sideways (m)	81 ± 40	
			High-intensity activity (m) (>18.1 km·h ⁻¹)	1,973 ± 623	

Table 2.7 (continued). Summary of the activity profile of soccer referees during match play

Competition	Tracking Technology	Sample Size	Measurement	Value	Reference
Danish Superliga	Manual video-based motion analysis	Referees = 27 Games = 43	Total distance (km)	10.1 ± 0.1	Krustrup and Bangsbo, 2001 (14)
			Walking (km) (6 km·h ⁻¹)	3.9 ± 0.1	
			Jogging (km) (8 km·h ⁻¹)	1.9 ± 0.1	
			Low-speed running (km) (12 km·h ⁻¹)	1.7 ± 0.1	
			Backwards running (km) (10 km·h ⁻¹)	0.9 ± 0.1	
			Moderate-speed running (km) (15 km·h ⁻¹)	1.1 ± 0.1	
			High-speed running (km) (18 km·h ⁻¹)	0.4 ± 0.0	
			Sprinting (km) (25 km·h ⁻¹)	0.2 ± 0.0	
			Standing (% game time) (0 km·h ⁻¹)	21.8	
			Walking (% game time) (6 km·h ⁻¹)	41.4	
			Low-intensity running (% game time) (6 – 12 km·h ⁻¹)	30.2	
			High-intensity running (% game time) (>15 km·h ⁻¹)	6.6	

Table 2.7 (continued). Summary of the activity profile of soccer referees during match play

Competition	Tracking Technology	Sample Size	Measurement	Value	Reference				
Italian Serie A and Serie B	Video-based motion analysis	Referees = 18 Games = 18	Total distance (m)	11,736 ± 1,604	D'Ottavio and Castagna, 2001 (113)				
			Standing still (% game time)	16.9					
			Low-intensity running (m) (<13 km·h ⁻¹)	4,174 ± 616					
			Medium-intensity running (m) (13.1 – 18.0 km·h ⁻¹)	2,585 ± 489					
			High-intensity running (m) (18.1 – 24.0 km·h ⁻¹)	1,556 ± 493					
			Maximal speed running (m) (>24.0 km·h ⁻¹)	608 ± 366					
			Walking forward (m)	889 ± 94					
			Walking backward (m)	68 ± 30					
			Running backward (m)	1,315 ± 569					
			Running sideways (m)	181 ± 117					
			High-intensity activity (m) (>13.1 km·h ⁻¹)	4,749 ± 1,055					
			European Cup	Video-based motion analysis		Referees = 13 Games = 13	Total distance (m)	11,218 ± 1,056	Castagna et al., 2004 (114)
							Low-intensity running (m) (<13 km·h ⁻¹)	4,879 ± 605	
							Medium-intensity running (m) (13.1 – 18.0 km·h ⁻¹)	2,562 ± 471	
High-intensity running (m) (18.1 – 24.0 km·h ⁻¹)	1,277 ± 398								
Maximal speed running (m) (>24.0 km·h ⁻¹)	366 ± 344								
Walking forward (m)	994 ± 184								
Walking backward (m)	42 ± 23								
Running backward (m)	989 ± 700								
Running sideways (m)	108 ± 91								
High-intensity activity (m) (>18.1 km·h ⁻¹)	1,642 ± 689								

Table 2.7 (continued). Summary of the activity profile of soccer referees during match play

Competition	Tracking Technology	Sample Size	Measurement	Value	Reference
FIFA U-17 World Cup	Video-based motion analysis	Referees = 11 Games = 12	Total distance (m)	11,059 ± 935	Mallo et al., 2007 (59)
			Standing still (m)	843 ± 120	
			(<1 m·s ⁻¹)		
			Walking (m)	2,402 ± 162	
			(1.01 – 2 m·s ⁻¹)		
			Jogging (m)	3,721 ± 579	
			(2.01 – 3.60 m·s ⁻¹)		
			Cruising (m)	2,684 ± 518	
			(3.60 – 5 m·s ⁻¹)		
			Sprinting (m)	1,405 ± 453	
(>5.01 m·s ⁻¹)					
High-intensity activity (m)	4,089				
(>3.60 m·s ⁻¹)					
English Premier League	Computer-based tracking	Referees = 19 Games = 254	Total distance (m)	11,622 ± 739	Weston et al., 2007 (106)
			High-intensity running (m)	787 ± 245	
			(>5.5 m·s ⁻¹)		

Table 2.7 (continued). Summary of the activity profile of soccer referees during match play

Competition	Tracking Technology	Sample Size	Measurement	Value	Reference
International, U-21 international, Champions League, UEFA Cup	Video-based motion analysis	Referees = 15 Games = 15	Total distance (km)	10.7 ± 0.9	Krustrup et al., 2009 (15)
			Standing (% game time)	21.9 ± 4.7	
			Walking (% game time)	40.2 ± 5.1	
			(6 km·h ⁻¹)		
			Jogging (% game time)	15.8 ± 2.9	
			(8 km·h ⁻¹)		
			Low-speed running (% game time)	9.3 ± 1.5	
			(12 km·h ⁻¹)		
			Sideways running (% game time)	0.2 ± 0.2	
			(10 km·h ⁻¹)		
			Backwards running(% game time)	5.3 ± 2.4	
			(10 km·h ⁻¹)		
			Moderate-speed running(% game time)	4.8 ± 1.5	
			(15 km·h ⁻¹)		
High-speed running (% game time)	2.1 ± 0.9				
(18 km·h ⁻¹)					
Sprinting (% game time)	0.4 ± 0.2				
(25 km·h ⁻¹)					
High-intensity running (km)	1.9 ± 0.6				
(>15 km·h ⁻¹)					

Table 2.7 (continued). Summary of the activity profile of soccer referees during match play

Competition	Tracking Technology	Sample Size	Measurement	Value	Reference
FIFA Confederations Cup	Video-based motion analysis	Referees = 9 Games = 9	Total distance (m)	10,218 ± 643	Mallo et al., 2009 (115)
			Standing still (m)	1,977 ± 187	
			(<1 m·s ⁻¹)		
			Walking (m)	2,184 ± 162	
			(1.01 – 2 m·s ⁻¹)		
			Jogging (m)	2,526 ± 230	
			(2.01 – 3.60 m·s ⁻¹)		
			Cruising (m)	1,611 ± 204	
			(3.60 – 5 m·s ⁻¹)		
Sprinting (m)	1,920 ± 399				
(>5.01 m·s ⁻¹)					
High-intensity activity (m)	3,531				
(>3.60 m·s ⁻¹)					
English Premier League	Computer-based tracking	Referees = 17 Games = 85	Total distance (m)	11,478 ± 580	Weston et al., 2009 (116)
			High-intensity running (m)	753 ± 231	
			(>5.5 m·s ⁻¹)		
English Premier League	Computer-based tracking	Referees = 18 Games = 236	Sprinting (m)	160 ± 78	Weston et al., 2011 (60)
			(>7.0 m·s ⁻¹)		
			Total distance (m)	11,280 ± 738	
English Premier League and Football League	Computer-based tracking	Referees = 59 Games = 1,269	High-intensity running (m)	716 ± 238	Weston et al., 2011 (107)
			(>19.8 km·h ⁻¹)		
			Sprinting (m)	153 ± 108	
English Premier League and Football League	Computer-based tracking	Referees = 59 Games = 1,269	(>25.2 km·h ⁻¹)		Weston et al., 2011 (107)
			Total distance (m)	11,770 ± 808	
			High-intensity running (m)	889 ± 327	
			(>19.8 km·h ⁻¹)		

Table 2.7 (continued). Summary of the activity profile of soccer referees during match play

Competition	Tracking Technology	Sample Size	Measurement	Value	Reference
America's Cup	1 Hz GPS (SPI Elite)	Referees = 7 Games = 7	Total distance (m)	10,197 ± 952	Barbero-Alvarez et al., 2012 (117)
			Standing still (m)	~59	
			(0 – 0.4 km·h ⁻¹)		
			Walking forward (m)	1,329 ± 146	
			(0.5 – 4 km·h ⁻¹)		
			Low-intensity running (m)	3,043 ± 337	
			(4.1 – 8 km·h ⁻¹)		
			Medium-intensity running (m)	3,127 ± 199	
			(8.1 – 13 km·h ⁻¹)		
			High-intensity running (m)	1,941 ± 644	
Spanish National Third Division	10 Hz GPS (MinimaxX v4.0)	Referees = 20 Games = 20	Total distance (m)	9,991 ± 657	Castillo et al., 2017 (118)
			High speed running (m)	2,783 ± 630	
			(>13 km·h ⁻¹)		
			Spanish National Third Division	10 Hz GPS (MinimaxX v4.0)	
Low walking (m)	820.2 ± 290.7				
(<3.60 km·h ⁻¹)					
Walking (m)	2,739.2 ± 365.3				
(3.61 – 7.20 km·h ⁻¹)					
Jogging (m)	3607.4 ± 659.3				
(7.21 – 13.0 km·h ⁻¹)					
Cruising (m)	2,114.6 ± 441.7				
(13.1 – 18.0 km·h ⁻¹)					
High speed running (m)	798.3 ± 310.2				
(>18.0 km·h ⁻¹)					
High intensity running (m)	2,901.8 ± 688.8				
(>13.0 km·h ⁻¹)					

2.4.2 Rugby union

Rugby union is a high-intensity intermittent collision sport involving short bouts of repeated HIR and collisions, separated by longer periods of low and moderate-intensity activity or rest (84, 120, 121). Games are 80 min in duration and are played between two teams of 15 players on a playing area ~6,400 m². Similar to Gaelic football and soccer, rugby union is officiated by a referee and two assistant referees, formerly known as ‘touch judges’, who are required to keep up with play at all times. At the elite level, rugby union referees are professional, and are typically supported by a television match official (122). While the activity profile and physiological demands of elite rugby players have been extensively reported, few studies have examined the activity of the referee (54).

2.4.2.1 Activity profile

One of the first studies to examine the activity profile of rugby union referees used manual video-based analysis and found that referees covered a total distance of 8.6 km during match play. The majority of game time was spent standing still or walking, ~20% was spent jogging and running, and ~1% involved sprinting (123). These values are comparable to a more recent study using 1 Hz GPS technology that reported a total distance of 8.0 km during match play with ~95% of game time spent at speeds $\leq 5.0 \text{ m}\cdot\text{s}^{-1}$ and ~1% at speeds $> 7.0 \text{ m}\cdot\text{s}^{-1}$ (124). In contrast, a total distance of 6.3 km was reported for elite Spanish rugby referees, yet consistent with previous studies most of the game time involved low intensity activity and ~10% at high-intensity ($> 18.0 \text{ km}\cdot\text{h}^{-1}$) (125). In the most comprehensive study to date, elite rugby union referees from eight countries were monitored using GPS technology during 205 competitive games at both international and

domestic level (122). The total distance covered during match play was 6.8 km. The majority of game time involved referees moving at speeds $<2.3 \text{ m}\cdot\text{s}^{-1}$ with 27% spent at a speed between $4.1 - 9.6 \text{ m}\cdot\text{s}^{-1}$. The lack of standardisation in the velocity thresholds associated with the movement categories makes it difficult to compare activity profiles between studies. However, published data indicate that like soccer referees, the majority of the distance covered by elite rugby union referees is at low and moderate speeds. A summary of the activity profile of rugby union referees during match play is presented in Table 2.8.

2.4.2.2 Physiological responses

Several studies have examined the HR response of elite rugby union referees during match play. However, similar to studies that examined movement patterns during match play, there is no uniformity in the HR ranges examined. The earliest study relativised HR_{max} using an incremental laboratory-based exercise test and reported a mean relative HR of 84% HR_{max} throughout the entire game (126). A comparable mean HR has been reported during match play in more recent studies (124, 125). To date, only one study has estimated the $\dot{V}\text{O}_2$ of elite rugby union referees during competitive games using the linear relation between HR and $\dot{V}\text{O}_2$ and reported a mean $\dot{V}\text{O}_2$ of 79% $\dot{V}\text{O}_{2\text{max}}$ (126). This is consistent with that reported for elite soccer referees (81%) (14). This finding, in conjunction with the activity profile and HR response, highlights the similarities in physical demands experienced by elite IFTS referees.

Table 2.8. Summary of the activity profile of rugby union referees during match play

Competition	Tracking Technology	Sample Size	Measurement	Value	Reference	
English Premiership	Manual video-based motion analysis	Referees = 9 Games = 19	Total distance (m)	8,581 ± 668	Martin et al., 2001 (123)	
			Standing still (% game time)	37.0 ± 11.0		
			Walking (% game time)	29.5 ± 7.2		
			Jogging (% game time)	12.8 ± 3.2		
			Running (% game time)	9.8 ± 2.3		
			Sprinting (% game time)	1.0 ± 0.4		
			Walking backwards (% game time)	9.9 ± 3.2		
Super Rugby	1 Hz GPS (SPI Elite)	Referees = 9 Games = 12	Total distance (m)	8,030 ± 506	Blair et al., 2018 (124)	
			Relative distance (m·min ⁻¹)	83 ± 5		
			Walking (% game time) (0.0 – 2.0 m·s ⁻¹)	76.6 ± 1.8		
			Jogging (% game time) (2.1 – 3.6 m·s ⁻¹)	10.9 ± 0.9		
			Running (% game time) (3.7 – 5.0 m·s ⁻¹)	8.2 ± 0.9		
			High speed running (% game time) (5.1 – 7.0 m·s ⁻¹)	4.3 ± 1.5		
			Sprinting (% game time) (>7.1 m·s ⁻¹)	0.1 ± 0.1		
			Total distance (m)	6,826		Bester et al., 2019 (122)
			Standing and walking (% game time) (<2.3 m·s ⁻¹)	52.4		
			Jogging (% game time) (2.3 – 4.1 m·s ⁻¹)	20.3		
Work zone (% game time) (4.1 – 9.6 m·s ⁻¹)	27.3					

Table 2.8 (continued). Summary of the activity profile of rugby union referees during match play

Competition	Tracking Technology	Sample Size	Measurement	Value	Reference
Spanish National League	1 Hz GPS (SPI Elite)	Referees = 10 Games = 30	Total distance (m)	6,322 ± 565	Suarez-Arrones et al., 2013 (125)
			Walking (m) (0.1 – 6.0 km·h ⁻¹)	2,357 ± 291	
			Jogging (m) (6.1 – 12.0 km·h ⁻¹)	1,524 ± 229	
			Low intensity running (m) (12.1 – 14.0 km·h ⁻¹)	656 ± 131	
			Medium intensity running (m) (14.1 – 18.0 km·h ⁻¹)	1,110 ± 212	
			High intensity running (m) (18.1 – 20.0 km·h ⁻¹)	347 ± 27	
			Sprinting (m) (>20.1 km·h ⁻¹)	328 ± 230	
			Walking (% total distance) (0.1 – 6.0 km·h ⁻¹)	37.3	
			Jogging (% total distance) (6.1 – 12.0 km·h ⁻¹)	24.1	
			Low intensity running (% total distance) (12.1 – 14.0 km·h ⁻¹)	10.4	
			Medium intensity running (% total distance) (14.1 – 18.0 km·h ⁻¹)	17.6	
			High intensity running (% total distance) (18.1 – 20.0 km·h ⁻¹)	5.5	
			Sprinting (% total distance) (>20.1 km·h ⁻¹)	5.2	

2.4.3 Rugby league

Rugby league is akin to rugby union but does not involve rucks and mauls (127, 128). It is played between two teams consisting of 13 players on a playing area similar to rugby union. Games are also 80 min in duration, played across two 40 min halves. Consistent with elite soccer and rugby union, the officials in rugby league at the elite level are professional, and primarily consist of a referee, and two touch judges (129). The Australian National Rugby League does however utilise a two-referee system with one referee described as the 'lead' and one as the 'pocket' alongside the two touch judges (127). Rugby league also involves a timekeeper and at the elite level, a video referee.

2.4.3.1 Activity profile

Early examinations of the activity profile of elite rugby league referees using video-based motion analysis reported a mean total distance of 6.7 km. Standing still, walking, and jogging accounted for a combined 64% of the total game time with sprinting constituting only 1% (130). More recently, elite referees were monitored using 5 Hz GPS technology during competitive games in the European Super League (129). The total and relative distance covered during match play was 9.0 km and $104 \text{ m}\cdot\text{min}^{-1}$, respectively. The majority of the distance was covered at a speed $\leq 4.0 \text{ m}\cdot\text{s}^{-1}$, with only 6% at a speed $> 5.5 \text{ m}\cdot\text{s}^{-1}$. Referees also performed 825 discrete movement efforts, of which the majority were $\leq 4.0 \text{ m}\cdot\text{s}^{-1}$ and 6% were $> 5.5 \text{ m}\cdot\text{s}^{-1}$ (129). In a more recent study using GPS with a higher sampling rate (10 Hz), referees in the same competition were found to cover only 7.1 km with 3% $> 5.5 \text{ m}\cdot\text{s}^{-1}$ (131). It is difficult to make direct comparison between studies as limited information was provided on the data collection period.

A single analysis of the Australian National Rugby League two-referee system, using 10 Hz GPS technology, reported a mean total distance for the lead and pocket referees of 7.4 km and 7.6 km, respectively (127). This corresponds to a relative distance for the lead and pocket referees of 81.8 m·min⁻¹ and 83.9 m·min⁻¹, respectively. Both the lead and pocket referees covered the majority of distance at low and moderate speeds (<4.0 m·s⁻¹) with only 1.9% and 1.8% covered at a speed >5.5 m·s⁻¹, respectively. Overall, the values reported for elite rugby league referees are broadly similar to those of elite players, reiterating the physical challenge posed refereeing at the elite level of IFTS (128, 132). A summary of the activity profile of rugby union referees during match play is presented in Table 2.9.

2.4.3.2 Physiological responses

One of the earliest studies examining the HR responses of rugby league referees during match play reported a mean HR of 84% HR_{max} relativised to peak in-game HR (133). Using the HR_{max} achieved during a laboratory-based incremental exercise test, the mean HR among European Super League referee's during competitive match play was also 84% HR_{max} with only 20% of game time spent <80% HR_{max} (129). A more recent study involving European Super League referees relativised HR_{max} using peak in-game HR and reported a mean HR of 79% HR_{max} (131). Lead and pocket referees in the Australian National Rugby League were found to have a mean HR of 83% HR_{max} and 85% HR_{max}, respectively using the in-game HR_{max} approach also (127).

Table 2.9. Summary of the activity profile of rugby league referees during match play

Competition	Tracking Technology	Sample Size	Measurement	Value	Reference
National Rugby League	Manual video-based motion analysis	Referees = 5 Games = 10	Total distance (km)	6.7 ± 0.4	Kay and Gill, 2003 (130)
			Walking (% total distance)	8 ± 3	
			Jogging (% total distance)	56 ± 4	
			Sprinting (% total distance)	2 ± 2	
			Sideways (% total distance)	3 ± 1	
			Backwards (% total distance)	31 ± 2	
European Super League	5 Hz GPS (MinimaxX)	Referees = 8 Games = 44	Total distance (m)	8,951 ± 746	O'Hara et al., 2013 (129)
			<0.5 m·s ⁻¹ (m)	294 ± 57	
			0.51 – 2.0 m·s ⁻¹ (m)	3,009 ± 402	
			2.01 – 4.0 m·s ⁻¹ (m)	3,717 ± 432	
			4.01 – 5.5 m·s ⁻¹ (m)	1,411 ± 231	
			5.51 – 7.0 m·s ⁻¹ (m)	395 ± 133	
			>7.01 m·s ⁻¹ (m)	120 ± 97	
			<0.5 m·s ⁻¹ (% total distance)	3.3 ± 0.7	
			0.51 – 2.0 m·s ⁻¹ (% total distance)	34.0 ± 2.5	
			2.01 – 4.0 m·s ⁻¹ (% total distance)	41.4 ± 2.4	
			4.01 – 5.5 m·s ⁻¹ (% total distance)	15.4 ± 2.0	
			5.51 – 7.0 m·s ⁻¹ (% total distance)	4.6 ± 2.1	
			>7.01 m·s ⁻¹ (% total distance)	1.3 ± 1.0	
			European Super League	10 Hz GPS (MinimaxV4)	
High-intensity running (m) (>5.5 m·s ⁻¹)	200.1 ± 148.6				
High-intensity running (% total distance) (>5.5 m·s ⁻¹)	2.8				

Table 2.9 (continued). Summary of the activity profile of rugby league referees during match play

Competition	Tracking Technology	Sample Size	Measurement	Value	Reference
Australasian National Rugby League	10 Hz GPS (MinimaxX S4)	Referees = 19 Games = 86	Total distance (m)	7,427 ± 775	Brightmore et al., 2016 (127)
			Relative distance (m·min ⁻¹)	81.8 ± 7.6	
			Standing (m)	374 ± 277	
			(<0.5 m·s ⁻¹)		
			Walking (m)	2,627 ± 168	
			(0.51 – 2.0 m·s ⁻¹)		
			Jogging (m)	3,311 ± 680	
			(2.01 – 4.0 m·s ⁻¹)		
			Running (m)	922 ± 325	
			(4.01 – 5.5 m·s ⁻¹)		
			High speed running (m)	129 ± 73	
			(5.51 – 7.0 m·s ⁻¹)		
			Sprinting (m)	13 ± 15	
			(>7.0 m·s ⁻¹)		
			Standing (% total distance)	5.8 ± 5.6	
			(<0.5 m·s ⁻¹)		
			Walking (% total distance)	36.0 ± 4.2	
			(0.51 – 2.0 m·s ⁻¹)		
			Jogging (% total distance)	43.8 ± 6.2	
			(2.01 – 4.0 m·s ⁻¹)		
Running (% total distance)	12.0 ± 3.4				
(4.01 – 5.5 m·s ⁻¹)					
High speed running (% total distance)	1.7 ± 0.9				
(5.51 – 7.0 m·s ⁻¹)					
Sprinting (% total distance)	0.1 ± 0.3				
(>7.0 m·s ⁻¹)					

2.4.4 Gaelic football

2.4.4.1 Activity profile

To date, no published studies have examined the activity profile of elite GFR. In comparison, a large number of studies have analysed the activity profile of elite players during competitive match play. On average, elite inter-county Gaelic football players cover a total distance of 8.2 – 8.9 km and reach running speeds in excess of $8.0 \text{ m}\cdot\text{s}^{-1}$ during match play (8, 9). Similar to players of other IFTS, the majority of the total distance is covered at speeds $<4.72 \text{ m}\cdot\text{s}^{-1}$ (35). HSR distances ($\geq 4.72 \text{ m}\cdot\text{s}^{-1}$) and sprinting distances ($\geq 6.11 \text{ m}\cdot\text{s}^{-1}$) account for ~20% and ~5% of the total distance, respectively (8). The 400 – 500 m of sprinting undertaken by players is accumulated over an average of ~40 sprints. Players also complete an average of ~180 accelerations (8, 9).

Using 4 Hz GPS units, midfielders were found to cover the greatest total and HSR distances ($\geq 4.72 \text{ m}\cdot\text{s}^{-1}$) and to complete more accelerations compared to any other playing position (8). Half-backs and half-forwards covered a greater total and HSR distance, and completed more accelerations than full-backs and full-forwards (8). In contrast, there was no difference in peak running speed between playing positions. These findings were comparable to those reported for elite Gaelic football players using 10 Hz GPS units during pre-season games (134). Independent of playing position, the mean relative distance during match play was $92.4 \text{ m}\cdot\text{min}^{-1}$. The mean HSR ($5.5 - 7.0 \text{ m}\cdot\text{s}^{-1}$) and maximal running distance ($>7.0 \text{ m}\cdot\text{s}^{-1}$) was $8.3 \text{ m}\cdot\text{min}^{-1}$ and $1.7 \text{ m}\cdot\text{min}^{-1}$, respectively. Several positional differences were also identified with full-backs covering less relative and HSR distance than all other playing positions. Full-forwards also covered less relative distance than half-

backs and half-forwards and less HSR distance than half-backs (134). Direct comparisons between these studies are however difficult. In addition to the dataset comprising only pre-season games, the sampling rate of the GPS units and movement category velocity thresholds employed in this study are different from those used previously in Gaelic football.

2.4.4.2 Physiological responses

Relatively few studies have examined the physiological responses of elite Gaelic football players during match play (135, 136). The earliest of these examined the HR and blood lactate responses in a cohort of sub-elite Gaelic football players during 6 competitive games (135). The mean relative HR was 81% during both the first and second half. Similarly, there was no difference in blood lactate levels between the first (4.3 mM) and second half (3.4 mM). Since blood samples were taken at half time and full time it is likely that the concentration of blood lactate at both time points was influenced by the activity profile in the final minutes of each half and therefore may not provide an accurate representation of the metabolic demands of match play. Likewise, no differences were found in the HR response between the first and second half or between the first and last 10 min period during 'friendly' games (136). Mean HR achieved during 'friendly' games may not adequately reflect the physiological demands during competitive inter-county competitions.

2.4.5 Temporal changes in activity profile during match play

Full-game match analysis provides a global measure of the activity profile of IFTS athletes and referees. However, failure to examine the temporal changes in activity profile may mask the decrements in running performance between halves and quarters of match play which can be viewed as evidence of fatigue. For example, IFTS referees have been found to be at a greater distance from decisions in the attacking areas of the pitch during the latter stages of games (15), and to make more errors in the second half (16).

2.4.5.1 Total distance

Mixed results have been reported for the temporal changes in total distance covered by intermittent IFTS referees. In soccer, decrements of 1 – 7% in total distance between the first and second half were found during both international and domestic level competitions, including the English Premier League and Football League and the Italian Serie A and Serie B (58, 104–106). A greater total distance was also covered in the first 15 min period than any other 15 min period of match play (6 – 8%) during both international and domestic level competition (59, 105). Interestingly, the distance of the referee from infringements in soccer was found to increase from the start to the end of the game, independent of a reduction in total distance covered (14).

In rugby league and rugby union, the majority of studies have reported no difference in the total distance covered by the referee between the first and second half of match play (122–124, 127, 129). Only one study involving elite rugby union referees found a 7% decrement in the distance covered between the first and second half of play (125). In this study, the distance covered in the first 10 min period of the game was also

found to be higher than any other 10 min period (125). Similarly, during the first half of play elite Super League referees were found to cover a greater total distance during the first 10 min period of the game than any other 10 min period in the first half by 18 – 21% (131). The greater activity of elite rugby referees during the opening passages of match play is akin to that of soccer referees.

Using 10 Hz GPS units during pre-season games, elite Gaelic football players covered a similar distance in the first and second half but the distance covered in the opening 15 min period of the games was higher than any other 15 min period by 9 – 12% (134). These findings were similar during inter-county games in both the NFL and AIC during which the total distance covered in the first quarter was greater than any other quarter, decreasing in a time dependent manner (9). No information on the between half differences was provided (9).

2.4.5.2 High speed activity

Similar to total distance, results of studies examining the temporal changes during match play in high-speed activity have been equivocal. A significant reduction in the high-speed activity of elite soccer referees has been found during games at both international and domestic level (14, 58, 59, 105). In contrast, despite a reduction in total distance between the first and second half, no differences were found in sprinting activity using manual video-based analysis (104) or HIR distance ($>5.5 \text{ m}\cdot\text{s}^{-1}$) using CBT (106) between the first and second half of English Premier League games. When comparing differences over shorter periods, HIA ($>3.60 \text{ m}\cdot\text{s}^{-1}$) was higher during the opening 15 min of the first half than any 15 min period of the second half (59). A similar pattern was reported for

elite Danish referees who completed more HIA ($\geq 4.2 \text{ m}\cdot\text{s}^{-1}$) in the opening 15 min of match play than in the last 15 min of the first half and the middle 15 min of the second half (15).

In rugby league, referees monitored using 5 Hz GPS units were found to perform 14% fewer high-intensity efforts ($>5.5 \text{ m}\cdot\text{s}^{-1}$) in the second half of European Super League games (129). A more recent study also involving European Super League referees did not support this finding, reporting no significant difference in the number of high-intensity efforts ($>5.5 \text{ m}\cdot\text{s}^{-1}$) across 10 min game periods when using 10 Hz GPS units, despite a decrement in total distance (131). Likewise, lead referees in the Australian National Rugby League exhibited no change in HSR ($5.5 - 7.0 \text{ m}\cdot\text{s}^{-1}$) or sprinting distance ($>7.0 \text{ m}\cdot\text{s}^{-1}$) between the first and second half (127).

In the earliest examination of the activity profile of elite rugby union referees using manual video-based motion analysis, no differences were found in the time spent running or sprinting between halves (123). More recently, using 1 Hz GPS units, no difference in HSR ($5.51 - 7.0 \text{ m}\cdot\text{s}^{-1}$) or sprinting distance ($>7.0 \text{ m}\cdot\text{s}^{-1}$) was found between the first and second half of Super Rugby matches (124). The greatest amount of time spent at high-speed was in the first 10 min period of match play (124). In contrast, elite rugby union referees monitored using 1 Hz GPS units were found to spend less time performing HIA and to complete 20% fewer sprints in the second half than the first half during both international and domestic level competitions including the Rugby World Cup and Six Nations tournament (122, 125).

The mixed results reported for both soccer and rugby referees make it difficult to discern the presence of fatigue while officiating intermittent IFTS. The findings are further

confounded by the type of monitoring device used, and the validity and reliability of each, with a number of methods including video-based motion analysis and GPS units sampling at ≤ 5 Hz susceptible to considerable measurement error during high-speed activity (5). It has been proposed that IFTS referees employ a 'pacing strategy' to maintain the necessary running performance in the latter stages of a game (13). Indeed, it was reported that referees who covered less total and HSR distance in the first half covered significantly more in the second half and vice-versa (106). However, given the unpredictable nature of match play, and the apparent influence of player activities on the movement of the referee (60), it is unclear to what extent the referee can choose to pace their activities.

In Gaelic football, using 4 Hz GPS units, elite players were found to complete $\sim 4\%$ less HSR distance ($\geq 4.72 \text{ m}\cdot\text{s}^{-1}$) during the second half, independent of playing position, with players in the midfield position experiencing the greatest decrement of 9% (8). Reductions in sprinting distances ($\geq 6.11 \text{ m}\cdot\text{s}^{-1}$) were also observed between halves independent of position, with half-backs and midfielders having the greatest decrement compared to other positions (8). In a similar study, both the HSR ($\geq 4.72 \text{ m}\cdot\text{s}^{-1}$) and sprinting distance ($\geq 6.11 \text{ m}\cdot\text{s}^{-1}$) and the number of accelerations all decreased from the first quarter of the game, independent of playing position, in a time-dependent manner (9). Midfielders were found to experience the greatest decrement in HSR distance and number of accelerations compared to any other position. Along with half-backs, midfielders also had the greatest decrement in sprint distance compared to any other position.

In contrast to the latter studies involving NFL and AIC games, only half-backs were found to experience a reduction in HSR ($\geq 5.5 \text{ m}\cdot\text{s}^{-1}$) in the fourth quarter of match play compared to any other period during pre-season games (134). The only decrement in maximum speed running distance ($\geq 7.0 \text{ m}\cdot\text{s}^{-1}$) across the quarters of match play was observed for midfielders in the fourth quarter (134). Differences in the competitive nature of the games and fitness level of the players during the pre-season phase may have contributed to the differences between studies (88). The various sampling rates of the GPS technology and lack of consistency in the movement category velocity thresholds also limits direct comparison between the studies. Nonetheless, in agreement with studies involving intermittent IFTS referees, the first quarter of elite Gaelic football match play appears to be the most intense period of the game.

2.4.6 Competitive level differences in activity profile

The standard of competition has been found to influence the activity profile of players during match play in a number of IFTS including soccer, rugby league and hurling. In particular, higher total and HSR distances were reported for elite players than sub-elite players (26, 137–139). As the activity profile of IFTS referees is similar to that of players, differences in competition standard may also influence the activity profile of the referee. Few studies have examined the influence of competitive level on the activity profile of IFTS referees.

When comparing the activity profile of elite referees during match play across divisions in domestic leagues, mixed results have been reported. Referees in the second tier of the Danish national league completed 21% more HSR distance ($18 - 25 \text{ km}\cdot\text{h}^{-1}$) and

performed 44% more HSR bouts than referees in the first division. In addition, there was no difference in the total distance covered (14). In contrast, elite English referees had a higher mean HR and a higher rating of perceived exertion (RPE) while officiating games in the Premier League compared to the Football League (110). Elite referees also covered a greater HSR distance during senior international games than during the FIFA Under-17 World Cup (140).

Referees from the top two tiers of the Italian domestic leagues (Serie A and Serie B) were found to cover a greater total and HIR distance ($18.1 - 24 \text{ km}\cdot\text{h}^{-1}$) and complete more HIA ($>18.1 \text{ km}\cdot\text{h}^{-1}$) than elite referees officiating international level games (114). The distance covered by the referees at the domestic level was however considerably higher than previously reported for the referee during Serie A and Serie B games (105). The large increase was attributed in part to the implementation of a supervised exercise training programme for elite referees in the Italian soccer league (114). It is difficult to quantify the effects of the training programme on the differences observed in the activity profile of the referee between domestic and international level as the study design did not include a control group. There was also no information provided on the games officiated by the referees at international level (114).

No difference was found in the total distance covered by elite Spanish soccer referees when officiating in the national division involving teams ranked in the top 10, teams in the bottom 10, and games between teams from the top and bottom 10 (141). In addition, the percentage of game time spent at high-intensity ($>13.0 \text{ km}\cdot\text{h}^{-1}$) and the HSR distance ($>18.0 \text{ km}\cdot\text{h}^{-1}$) did not differ between games involving teams ranked in the top

10, bottom 10 and games between teams from the top and bottom 10. While officiating games involving top 10 ranked teams, referees spent more time at low walking speed ($<3.6 \text{ km}\cdot\text{h}^{-1}$). However, they completed a higher percentage of high-intensity accelerations ($2.0 - 2.5 \text{ m}\cdot\text{s}^{-2}$) when officiating games involving top 10 ranked teams than games between teams ranked in the bottom 10 (141).

Activity data were collected from five separate Gaelic football teams across five inter-county seasons, using 4 Hz GPS technology, to examine the impact of team rank on the activity profile of elite players, (10). Using the Elo rating system, players classified as being from 'Tier 1' teams covered a greater total (6%) and HSR distance ($\geq 4.72 \text{ m}\cdot\text{s}^{-1}$) (9%) than players from 'Tier 2' teams. Players from 'Tier 1' and 'Tier 2' teams covered less HSR distance (12 – 20%) when competing against 'Tier 4' teams (10). A more recent analysis across playing divisions found that players from a Division 3 team completed a greater total and relative HSR distance ($\geq 4.72 \text{ m}\cdot\text{s}^{-1}$), number of HSR bouts, number of accelerations, and spent a greater percentage of game time at high-speed than players from a Division 1 team during games in the NFL and AIC (12). Differences were observed in a number of technical factors such as the defensive organisation and shot efficiency between the Division 1 and Division 3 team, likely reflective of differences in the tactical approach and/or skill level which may in turn have contributed to the differences in activity (12).

While no study has directly compared the activity profile of elite Gaelic football players between the NFL and the AIC, seasonal variations have been reported (11). The total distance covered by players from Division 1 – 3 teams during games in August and

September was higher than any other month of the inter-county season. The HSR distance ($\geq 4.72 \text{ m}\cdot\text{s}^{-1}$) was also higher during inter-county games in August and September compared to any other month. The higher total and HSR distance in August and September coincide with the final stages of the AIC, regarded as the highest level of competition within Gaelic football (11). There are however a number of limitations with this study. Firstly, the intra-unit reliability for HSR of the GPS units used in this study have a CV of 8%. Secondly, the authors fail to include any contextual information in their analysis other than month of the year. For instance, teams from the lower divisions of the NFL are unlikely to compete in the latter stages of the AIC. Given that differences have been found in HSR distance between high and low ranking teams (10), the lack of information regarding the team rank in each month makes it difficult to draw any solid conclusions. In addition, the statistical analysis did not control for other contextual factors such as competition structure (i.e., round robin, knockout), match importance, and opposition quality within the NFL and AIC that may have influenced the activity profile of players.

The relatively small sample sizes, differences in tracking technology, and varying movement category velocity thresholds make it difficult to make definitive conclusions on the impact of competitive level on the activity profile of elite IFTS referees. Regardless, it is important to develop a clear understanding of the impact that competitive level differences may have on the activity profile of elite referees. This will help to ensure that referees at all levels possess the necessary fitness requirements to cope with the physical demands of match play (110).

2.5 Influence of contextual factors on the referee activity profile

The influence of several contextual factors has been examined to better understand the activity profiles of elite IFTS referees during match play (13). These include age, experience level, and physical fitness of referees as well as the activity profile of players. Studies to date have been limited to soccer referees. In 2010, the GAA introduced an age limit of 50 years for match officials on both the NFL and AIC panels. Similar age restrictions have been in place in soccer, although in some countries such as England, these were successfully contested (142). In recent years, FIFA removed the maximum age restriction on international level referees, although they reserve the right to request additional fitness assessments where necessary (143). As IFTS referees are typically 15 – 20 years older than the players of their respective sport, the impact of ageing on both the activity profile and physical fitness levels is of interest.

2.5.1 Age and experience level

Elite soccer referees categorised as ‘young’ (31 – 36 years) were found to cover more total (6 – 8%) and HIR distance ($>5.5 \text{ m}\cdot\text{s}^{-1}$) (15 – 40%) and complete a greater number of sprints ($>25.2 \text{ km}\cdot\text{h}^{-1}$) (17 – 54%) than referees categorised as ‘intermediate’ (37 – 42 years) and ‘older’ (43 – 48 years) during competitive games in the English Premier League (142). The ‘older’ referees also covered less total and HIR distance and completed less sprints than referees in the ‘intermediate’ group and had a lower peak running speed than both referees in the ‘young’ and ‘intermediate’ groups. An inverse correlation was also found between age and total distance ($r = -0.52$), HIR distance ($r = -0.53$), and sprint count ($r = -0.53$). Interestingly, there was no relation between age and distance from the

ball or from foul play between the 'young' and 'older' groups. It was hypothesised that the reduction in total and HIR distance without a concomitant increase in the distance from the ball or foul play may be due to the greater experience level of older referees. More experienced referees may anticipate the pattern of play better than less experienced referees, resulting in more efficient movement around the playing field (142).

The influence of refereeing experience on the activity levels of elite English soccer referees has previously been evaluated (107, 110). There was no difference in the mean HR and RPE during match play between referees with ≤ 4 seasons (low experience) and >4 seasons (high experience) officiating in the Premier league (110). Similarly, no difference was found between low and high experience referees in the game to game variation of total and HSR distance, number of sprints, peak running speed or distance from both the ball and foul play during games in the English Premier League and Football League (107). The absence of a difference in the game to game variation between experience levels indicates that large variations in the activity profile of the referee occur regardless of age or experience level.

2.5.2 Ageing and physical fitness

It has been speculated that the reduced total and HSR distance observed for older referees may be due in part to lower levels of physical fitness (142). Findings from studies that have examined age-related differences in physical fitness among soccer referees have been equivocal (144–146). Elite Italian referees, classified as 'young' (31 – 35 years), had a higher countermovement jump than both 'average age' (36 – 39 years), and 'older' (40 – 45 years) referees (145). The 'young' referees also performed better in a 200 m sprint

than referees in the 'older' group. In contrast, there was no difference in 50 m sprint time or 12 min run distance between any of the age groups. Using a field-based incremental exercise test, 'young' referees were found to have a 23% higher estimated $\dot{V}O_{2max}$ than 'older' referees. However, the 'older' referees attained a 5% higher speed at a FBLC of 2 mM than 'young' referees (145).

Among elite 'young' (27 – 32 years), 'average age' (33 – 38 years), and 'older' (39 – 45 years) Spanish soccer referees, 50 m sprint time was found to be better in the 'young' referees compared to the referees in the 'older' group (144). However, there was no difference in 200 m sprint time, $\dot{V}O_{2max}$ or 12 min run distance between groups. A more recent study examined selected fitness indices among a panel of national and provincial level Spanish referees who were divided into two age groups (≤ 35 years or > 35 years), independent of current standard of officiating (146). Performance in 20 m and 30 m sprint time, modified agility test time, and Yo-Yo Intermittent Recovery Test Level 1 (YIRT1) distance was significantly better in the ≤ 35 years group than the older group (146). These results should however be interpreted with caution as no information was provided on the officiating standard of the referees within each group.

The findings from these studies make it difficult to conclude whether changes in the activity profile of elite IFTS referees may be influenced by age-related decrements in physical fitness. Importantly, study participants regularly undertook supervised exercise training programmes that may negate, at least in part, age-related decrements in physical fitness (147).

2.5.3 Physical fitness and activity during match play

A minimum level of physical fitness is required to officiate IFTS (13, 54). Regular physical fitness testing is therefore commonly used by governing bodies of IFTS as part of their referee selection criteria (13, 54). These tests are primarily field-based and permit the testing of multiple referees at the one time. There is a strong relation between performance in select field-based tests and the activity profile of elite soccer referees during competitive match play. A significant relation was found between 12 min run distance, YIRT1 distance and laboratory-based $\dot{V}O_{2\max}$ of elite Danish referees with both total ($r = 0.48 - 0.66$) and HIR distance ($>15 \text{ km}\cdot\text{h}^{-1}$) ($r = 0.46 - 0.75$) during match play (14). More recently, a significant relation was found between YIRT1 distance and both the HIR distance ($>3.6 \text{ m}\cdot\text{s}^{-1}$) ($r = 0.42$) and HSR distance ($>5.0 \text{ m}\cdot\text{s}^{-1}$) ($r = 0.59$) of Spanish third division referees (119). A significant relation was also found between YIRT1 distance and the number of high-intensity accelerations ($2.0 - 2.5 \text{ m}\cdot\text{s}^{-2}$) ($r = 0.41$) and decelerations ($-2.0 - -2.5 \text{ m}\cdot\text{s}^{-2}$) ($r = 0.44$) performed by the referee (119).

Since its inception, the YIRT1 has become one of the most extensively used, and widely studied field-based fitness tests used to examine the aerobic fitness levels of IFTS players and referees (148, 149). The test involves exercise at progressively increasing intensities and can elicit maximal $\dot{V}O_2$ and HR (148). Benefits of the YIRT1 include the relative ease to administer and minimal equipment requirements. The YIRT1 also has good validity and test-retest reliability across a number of sports and competitive levels (148–150).

2.6 Summary

Referees in Gaelic football are required to keep up with play at all times irrespective of the dynamic intermittent nature of match play. Coupled with the large playing area, this requires a high level of physical fitness. To date, no studies have examined the activity profile of elite GFR during match play. Player tracking technology has advanced considerably in recent decades. In particular, GPS and GNSS technology sampling at a rate of ≥ 10 Hz have good validity and reliability for measures of total distance and distance covered at a range of movement speeds. These units also provide a relatively cost and time effective, non-invasive method to evaluate the activity profile of the referee during competition.

The activity profile of soccer and rugby referees during match play is largely similar to that of the players. However, a major weakness of these studies is the lack of standardisation of the movement category velocity thresholds. Arbitrary, player-based velocity thresholds are commonly used when examining the activity profile of IFTS referees which may result in an under or overestimation of the distance covered within each movement category. Future studies need to address these limitations prior to the analysis of the activity profile of IFTS referees.

The first period of match play in soccer and rugby has been identified as the most physically demanding for the referee. In addition, the activity of the referee is reduced in the second half compared to the first half. Examinations of the temporal changes during match play are important as large decrements may be indicative of an impaired ability to keep up with play during the latter stages of games. The activity profile of elite IFTS

referees is also thought to be influenced by several factors including competitive level, age, experience, physical fitness and the activity of the players. However, few studies have examined these factors, all of which have involved soccer referees. A greater understanding of the influence of competitive level and contextual factors on the activity profile of the referee would help to ensure that GFR, and other IFTS referees at all levels are optimally prepared for the physical demands of match play.

CHAPTER III

STUDY 1

IDENTIFICATION OF MOVEMENT CATEGORIES AND ASSOCIATED VELOCITY

THRESHOLDS FOR ELITE GAELIC FOOTBALL REFEREES

3.1 Introduction

3.1.1 Rationale

GPS and GNSS technology provide large quantities of data on the location at a specific time point from which individual velocities and distances can be quantified (5). These distances are typically summarised into a number of velocity-based movement categories that vary in intensity and are associated with verbal descriptors such as low, moderate and high-speed (7). Although this approach is common in both applied and research settings, no consensus currently exists regarding the optimum number of categories or their velocity thresholds. Indeed, categories are often arbitrary, based on manufacturer thresholds (128, 151), with no apparent empirical evidence on their validity for use within IFTS.

A number of studies have examined the activity profile of IFTS referees, particularly in soccer and rugby (13, 54). These studies have however applied arbitrary movement category velocity thresholds originally adopted for the analysis of the activity profiles of elite male players (120, 128, 151). While such categories enable direct comparison between groups, the efficacy of using the same categories for players and referees is questionable given the differences in age and physical capacity (17, 18, 60). Elite IFTS referees are typically 15 – 20 years older than elite players. Failure to account for age-

related differences in physical fitness such as the reduction in muscle mass and strength, and $\dot{V}O_{2max}$, which can decline by ~10% per decade after the age of 20, may result in an underrepresentation of the physical demands experienced by elite IFTS referees (147).

Unsupervised clustering techniques present a viable alternative to the application of arbitrary movement categories (52). Spectral clustering is a graph-based approach used to divide data points into groups such that data points in the same group are heavily connected and data points in different groups are not connected (100). It is a popular method of clustering due to its ability to overcome some of the limitations of traditional clustering techniques such as *k*-means. Using spectral clustering, three unique velocity thresholds were generated for elite women's soccer players (52). These thresholds resulted in meaningful differences in the distance covered at high and very high-speed compared to arbitrary velocity thresholds and thresholds derived from other machine learning techniques (52). Similarly, spectral clustering was used in elite youth female soccer to generate velocity thresholds, yielding a set of unique values for under-14, under-16 and youth (under-16 and under-14 combined) players that resulted in significant differences in the distance covered in each category between groups (94). The purpose of this study is to use an unsupervised clustering technique to identify movement categories and associated velocity thresholds for elite GFR.

3.1.2 Study aims

1. To use an unsupervised clustering technique to identify the appropriate number of movement categories for elite GFR during inter-county match play
2. To use an unsupervised clustering technique to generate the velocity threshold associated with each movement category
3. To compare the strength of association between the raw activity data and both the newly generated movement category velocity thresholds and a set of arbitrary velocity thresholds commonly used in the analysis of IFTS

3.1.3 Study hypotheses

1. The optimal number of movement categories identified using an unsupervised clustering technique will be similar to the number used previously in the analysis of the activity profiles of IFTS players and referees
2. The newly generated movement category velocity thresholds will be lower than the arbitrary velocity thresholds commonly used in the analysis of IFTS players and referees
3. In comparison to arbitrary velocity thresholds, the level of association between the raw velocity data and the newly generated movement category velocity thresholds will be significantly greater

3.2 Methodology

3.2.1 Overview of study design

Elite GFR, recruited from the NFL and AIC panels, were monitored using GPS and GNSS technology during inter-county games in both the NFL and AIC between 2016 and 2019. The games examined include each of the four divisions of the NFL and all three phases of the AIC. Activity data from each game were subsequently downloaded and analysed using a two-stage unsupervised clustering technique. This algorithm was specifically designed to identify the appropriate number of movement categories and the respective velocity thresholds for elite GFR. The strength of association between the raw velocity data was then compared with the newly generated movement category velocity thresholds and a set of arbitrary velocity thresholds. The distance within each corresponding movement category was compared also.

3.2.2 Participants

3.2.1.1 Participant recruitment

Ethical approval was obtained from Dublin City University Research Ethics Committee (Appendix 1) in accordance with the Declaration of Helsinki. Elite GFR selected to officiate as part of the NFL and AIC panels during the 2016 – 2019 inter-county seasons were eligible to participate. Prior to the commencement of each season, the referees were provided with a detailed presentation on the study purpose and individual requirements associated with participation. While the inclusion criteria were not specifically limited to males, referees on the national panel during the data collection period were all males.

3.2.1.2 Participant profile

Forty-one elite inter-county GFR [mean \pm standard deviation (SD); age: 38.6 ± 5.8 years; height: 175.7 ± 6.5 cm; weight: 79.8 ± 9.1 kg; body mass index (BMI): 25.8 ± 2.1 kg·m²] provided written informed consent to participate in the study. Referees included in the study had a median (range) of 5.8 (0.0 – 19.0) years' experience officiating at national level and 1.0 (0.0 – 14.9) years officiating in the AIC.

3.2.3 Anthropometry

Participants wore shorts and a light t-shirt and removed their shoes and socks prior to the assessment of their stature and body mass. Stature was measured to the nearest 0.1 cm using a portable stadiometer (SECA 213, Hamburg, Germany). Body mass was measured to the nearest 0.1 kg using a portable digital scale (SECA 877, Hamburg, Germany). Prior to the measurement of body mass participants were directed to void their bladder. BMI was calculated by dividing the body mass in kg by height in m².

3.2.4 Data collection

Data were collected during 338 competitive inter-county games. GPS/GNSS units sampling at 10 Hz (STATSports, Newry, Ireland) were worn midway between the scapulae in a custom-made undergarment that was tightly fitted to reduce movement during each game. Participants were familiarised with fitting the units into the undergarment and the correct operating procedures. To establish a satellite lock, the GPS/GNSS units were activated a minimum of 15 min prior to the start of each game (5).

STATSports 10 Hz Viper and 10 Hz Apex units were worn by the referees during the 2016 – 2017 and 2018 – 2019 playing seasons, respectively. The Viper and Apex units have

a mean bias of 1.1 – 2.0% for distance covered during a 400 m lap of an athletics track, 2.3 – 2.7% for the distance covered during a 128.5 m team sport circuit, 1.1 – 1.3% for the distance covered during a 20 m run, and 1.8 – 2.4% for peak running speed over 20 m (45, 46). The intra-unit reliability, expressed as the CV, of the Viper units was 1.6%, 0.8% and 0.4% for distance on the athletics track, team sport circuit and 20 m run, respectively, and 0.7% for peak running speed over 20 m. The inter-unit reliability of the Apex units for total distance and distance covered at a range of speeds, including speeds $>5 \text{ m}\cdot\text{s}^{-1}$, ranged from 0.3 – 1.3% CV (48). Additionally, both models have good inter-unit reliability (CV $<5\%$) for peak running speed (47). The validity and reliability of the Viper and Apex units is superior to units operating at a lower sampling rate (5). Given the high levels of measurement accuracy and the similarities between the intra and inter-unit reliability, the GPS/GNSS units in the present study were not designated solely to one referee which has previously been recommended to reduce error due to inter-unit reliability (5).

3.2.5 Data processing

The data collected from each game were stored on the GPS/GNSS unit and later downloaded to the manufacturer's software. Each individual data file was subsequently cleaned such that the first and second halves, inclusive of additional time at the end of each half, could be viewed independent of the warm-up and half time periods. The raw data for each half were then exported to analyse the measurement accuracy at each time point and to quantify the distances and speeds using Python (v.3.7) programming language (Python Software Foundation, Wilmington, DE, USA).

In an effort to maximise the validity of the data files, data points were excluded from the analysis if the instantaneous velocity was $>10 \text{ m}\cdot\text{s}^{-1}$, instantaneous acceleration was $>6 \text{ m}\cdot\text{s}^{-2}$ or instantaneous deceleration was $>6 \text{ m}\cdot\text{s}^{-2}$ (52, 53). As there is currently no published data regarding the maximal sprint speed or acceleration capabilities of elite GFR, these thresholds were adopted from previous studies involving both male and female IFTS athletes (52, 53, 152). Information regarding the number of satellites connected to the GPS unit and the HDOP at a given time point was not available for data files collected using Viper units. The information was however available for all data files collected using the Apex units. Data points from these files were excluded from the analysis if the HDOP was >2.0 or if the number of satellites locked onto the unit was <8 (32, 52). No 'gold standard' criteria for the number of satellites or the value of HDOP are available within the scientific literature. Rather, inclusion of such criteria has been strongly recommended to improve reporting accuracy and transparency (32). Where a data point was excluded, instantaneous velocity was imputed based on the values before and after it. Match files in which excluded data accounted for $>3\%$ of the game time were removed from the analysis ($n = 5$). This resulted in a final dataset of 333 full game data files with a median of 6 full game data files per referee (mean = 8.1 games; range: 1–25 games). A breakdown of the data files collected during games in the NFL and AIC is presented in Figure [3.1](#).

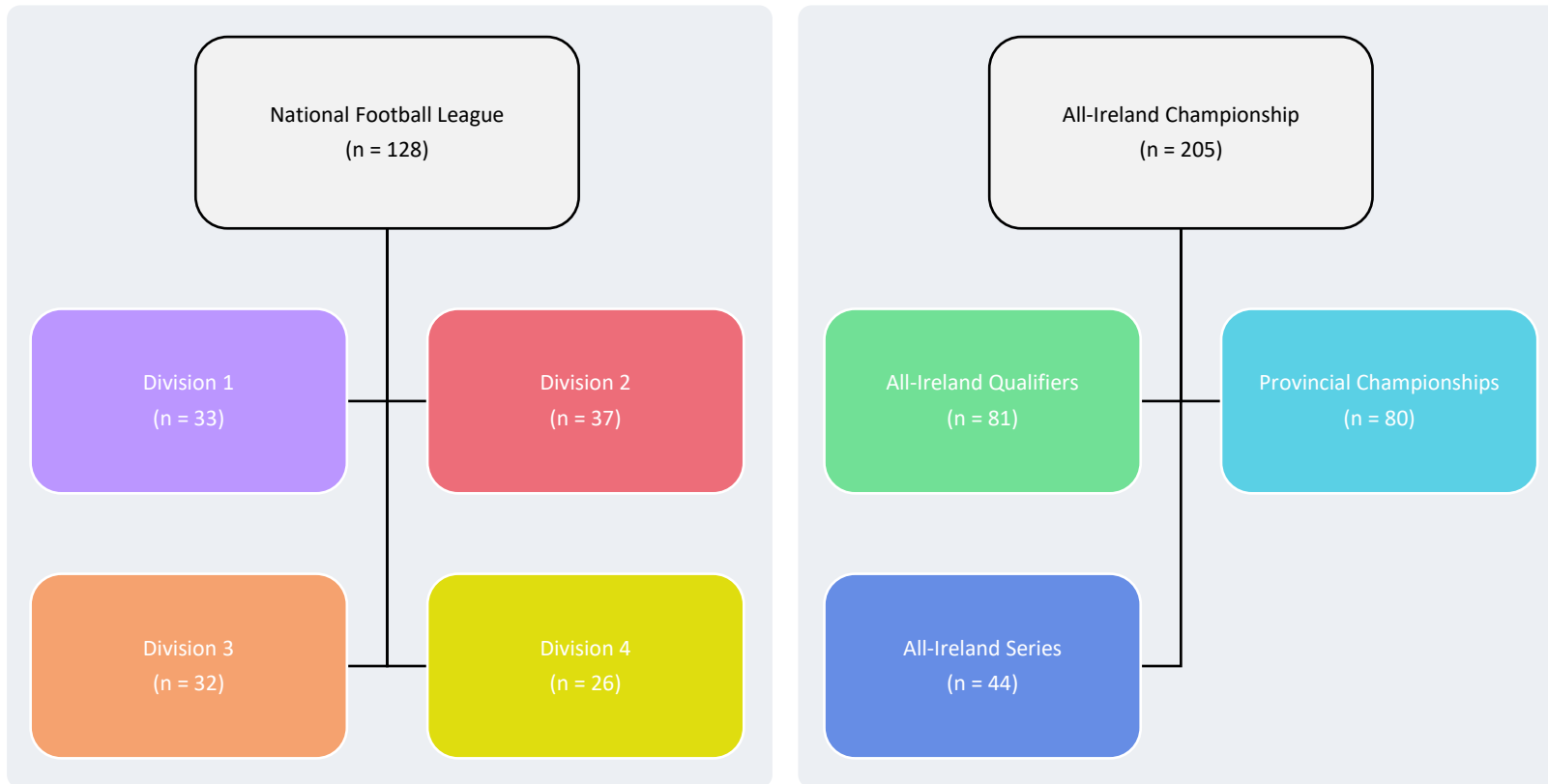


Figure 3.1. Breakdown of data files collected from games in both the NFL and AIC.

3.2.6 Unsupervised clustering

To generate a set of movement category velocity thresholds, the raw data files collected using GPS/GNSS technology were analysed using an unsupervised clustering technique in two distinct stages. This technique was used to convert continuous velocity measurements into categorical variables at the points which represent the minimal number of traversals. The first stage involved determining the number of thresholds to be generated. During this stage, the raw velocity measurements from each data file were merged to produce a single graph. A clustering technique was then applied repeatedly to this graph such that the optimal number of partitions within the dataset could be discerned. The second stage involved generating a graph for each respective data file and computing the values of each partition. The values for each data file were then used to derive group-based categories.

3.2.7 Clustering technique

Spectral clustering requires the computation of a similarity graph, which is a projection of velocity data onto a low-dimensional space and the use of a clustering technique to form categories (153). In this approach, the change in velocity from one time point to the next is considered to be a traversal on a similarity graph. The vertex set $V = \{v_1, \dots, v_n\}$ of this undirected graph represents the range of velocities from $0 \text{ m}\cdot\text{s}^{-1}$ to $10.0 \text{ m}\cdot\text{s}^{-1}$ in increments of $0.1 \text{ m}\cdot\text{s}^{-1}$. The similarity graph is represented by an adjacency matrix, W . This is a symmetric matrix in which each traversal from one velocity to another (v_i, v_j) increments the edge between the velocities which represent an element in the matrix, w_{ij} . From the adjacency matrix a diagonal matrix, D , is subsequently formed where each

element of D is equivalent to the sum of the weights of each column or row, with the remaining off diagonal elements set to zero (Eq.1).

$$d_i = \sum_{j=1}^n w_{ij} \quad (\text{Eq.1})$$

Using the diagonal and adjacency matrices, the normalised graph Laplacian, L^* , was then generated where D , W , and I are the diagonal, adjacency and identity matrices respectively, and $L = D - W$ (Eq.2).

$$L^* = D^{-\frac{1}{2}} L D^{-\frac{1}{2}} = I - D^{-\frac{1}{2}} W D^{-\frac{1}{2}} \quad (\text{Eq.2})$$

The eigenvalues and eigenvectors of the normalised graph Laplacian were then computed. For a matrix A , if a non-zero vector x exists and a scalar λ such that $Ax = \lambda x$ then x is said to be an eigenvector of A with corresponding eigenvalue λ . The number of eigenvalues of a graph Laplacian is equivalent to the number of velocities in the vertex set, V , each of which has a corresponding eigenvector.

3.2.7.1 Number of categories (Stage 1)

A normalised graph Laplacian with k connected components has k eigenvectors with an eigenvalue of zero. If the graph is fully connected, the elements of the first eigenvector will all be equal with a corresponding eigenvalue of zero, implying that all values are in one group (154). It is expected that velocity data are fully connected as it is not possible to get to one velocity without traversing through the range of lower velocities first. Therefore, to derive categories from the dataset, a set of partition vectors were selected from the remaining eigenvectors which corresponded to the lowest eigenvalues. Each element in a partition vector represents a velocity in the matrix. If two velocities have similar values in many partition vectors, then they likely belong to the same category

(154). As a result, Euclidean k -means clustering was then applied to identify the velocity thresholds for the dataset, with k equal to the number of partition vectors (Figure [3.2](#)) (100).

To determine the value for k , the number of clusters are varied and the distortion score (within-cluster sum of squares) is computed. The values are then plotted and the point of inflection selected as the most appropriate (98). This approach is known as the elbow method and is commonly used in cluster analysis to determine the number of categories (98). In the present study, the raw velocity data from each game was merged into a single unified similarity graph. The spectral clustering technique outlined above was then applied to the unified similarity graph for a range of k values (1 – 8) and plotted to identify the point of inflection (98).

Spectral clustering treats each velocity as a category, disregarding the rank order (52). In this regard, $1.0 \text{ m}\cdot\text{s}^{-1}$ may be grouped with $6.0 \text{ m}\cdot\text{s}^{-1}$. To overcome this, a β -coefficient of 0.1 was applied to the diagonal matrix to form a smoothed matrix, S which was subsequently used in place of the diagonal and adjacency matrices in [Eq.2](#) such that $L^* = I - S$ (52). The smoothed matrix was calculated as outlined in [Eq.3](#) where S , D , and W are the smoothed, diagonal, and adjacency matrices. The R is a $n \times n$ matrix that is all zeroes except for ones on the upper and lower diagonals, and D_R is a diagonal matrix containing the row sums of R .

$$S = (1 - \beta)D^{-1}W + \beta D_R^{-1}R \quad (\text{Eq.3})$$

Application of the β -coefficient to the diagonal matrix strengthens the relation between the diagonal elements and their adjacent points ensuring that velocities with no

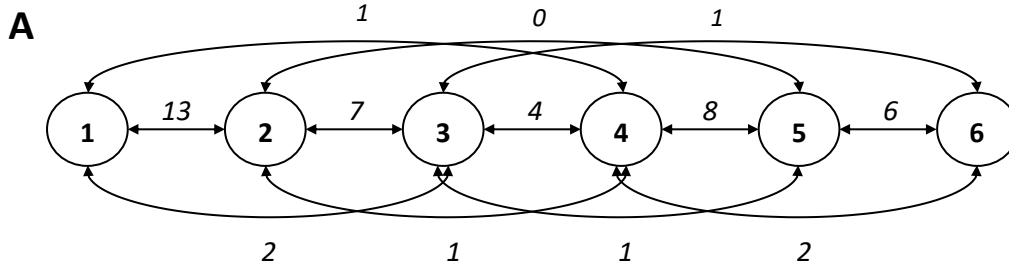
connected edges cannot be clustered together. The value of the β -coefficient was the lowest value that resulted in ordered partitions.

3.2.7.2 Category formation (Stage 2)

Having identified the most appropriate value of k , the second stage of the unsupervised clustering technique involved determining the value for each of the k clusters within the data files. Spectral clustering was applied to each data file separately using the value of k discerned in stage one to determine the value of each threshold. Group-based categories were then formed using the mean value of each partition from the individual data files.

3.2.8 Category evaluation

To assess if the newly generated movement category velocity thresholds reflected the raw velocity data, a regression analysis was performed on a subset of data files between the raw velocities at each time point and the median value of each movement category. The coefficient of determination (r^2) was then used to estimate how much variance in the raw data was explained by the newly generated movement category velocity thresholds. The subset of data files in the analysis were selected by partitioning data files into three even groups based on the peak running speed. Ten games from each group were subsequently chosen at random using a random number generator. The variance explained by the newly generated thresholds was compared to the arbitrary thresholds of 0.2, 2.0, 4.0, 5.5 and 7.0 m·s⁻¹ for standing, walking, jogging, running, HSR and sprinting, respectively. These thresholds are frequently used in the analysis of IFTS players and referees (107, 127, 129, 155).



$$W = \begin{bmatrix} 0 & 15 & 2 & 1 & 0 & 0 \\ 15 & 0 & 7 & 1 & 0 & 0 \\ 2 & 7 & 0 & 4 & 1 & 1 \\ 1 & 1 & 4 & 0 & 8 & 2 \\ 0 & 0 & 1 & 8 & 0 & 6 \\ 0 & 0 & 1 & 2 & 6 & 0 \end{bmatrix}$$

$$D = \begin{bmatrix} 18 & 0 & 0 & 0 & 0 & 0 \\ 0 & 23 & 0 & 0 & 0 & 0 \\ 0 & 0 & 15 & 0 & 0 & 0 \\ 0 & 0 & 0 & 16 & 0 & 0 \\ 0 & 0 & 0 & 0 & 15 & 0 \\ 0 & 0 & 0 & 0 & 0 & 9 \end{bmatrix}$$

$$L = \begin{bmatrix} 18 & -15 & -2 & -1 & 0 & 0 \\ -15 & 23 & -7 & -1 & 0 & 0 \\ -2 & -7 & 15 & -4 & -1 & -1 \\ -1 & -1 & -4 & 16 & -8 & -2 \\ 0 & 0 & -1 & -8 & 15 & -6 \\ 0 & 0 & -1 & -2 & -6 & 9 \end{bmatrix}$$

$$L^* = \begin{bmatrix} 1.000 & -0.850 & -0.100 & -0.050 & 0.000 & 0.000 \\ -0.637 & 1.000 & -0.324 & -0.039 & 0.000 & 0.000 \\ -0.120 & -0.470 & 1.000 & -0.290 & -0.060 & -0.060 \\ -0.056 & -0.056 & -0.275 & 1.000 & -0.500 & -0.113 \\ 0.000 & 0.000 & -0.060 & -0.530 & 1.000 & -0.410 \\ 0.000 & 0.000 & -0.100 & -0.200 & -0.700 & 1.000 \end{bmatrix}$$

B

Eigenvector 1 – [0.408, 0.408, 0.408, 0.408, 0.408, 0.408]

Eigenvector 2 – [0.428, 0.387, 0.103, -0.320, -0.510, -0.543]

Figure 3.2. Visual example of the unsupervised clustering technique. Adjacency (W), diagonal (D), Laplacian (L) and normalised Laplacian (L^*) matrices are formed using the traversals between velocities (A). The first two eigenvectors, corresponding to the two smallest eigenvalues of the normalised Laplacian are also shown (B). Euclidean k-means clustering applied to the second eigenvector would result in the formation of two unique clusters i.e., [1,2,3] and [4,5,6].

3.2.9 Statistical analysis

Statistical analysis was completed using the Statistical Package for the Social Sciences (SPSS) (v.25) (IBM, Chicago, IL, USA). Data are presented as mean \pm SD, unless otherwise stated. The distance covered in each movement category and the variance in the raw data accounted for using the newly generated velocity thresholds was compared to the distance covered in a corresponding set of arbitrary movement categories with velocity thresholds of 0.2, 2.0, 4.0, 5.5 and 7.0 m·s⁻¹ using a paired samples t-test. Prior to the analysis, normality assumptions were examined. Estimates of effect size (ES) were calculated for within-group comparisons as outlined by Lakens et al., (156). The significance level was set at $\alpha \leq 0.05$ for all tests.

3.3 Results

3.3.1 Movement categories

The value for k which corresponded to the inflection point was five (Figure [3.3](#)). The mean \pm SD for each velocity threshold was 0.70 ± 0.09 , 1.66 ± 0.19 , 3.28 ± 0.41 , 4.87 ± 0.61 , 6.49 ± 0.50 m·s⁻¹. Six unique movement categories were subsequently formed and are presented in Table [3.1](#) alongside the corresponding verbal descriptor.

3.3.2 Category evaluation

The results of the regression analysis spanning the three groups generated from the distribution of peak running speed are summarised in Table [3.2](#). Across the subset of games, the newly generated velocity thresholds accounted for a larger proportion of the variation in the raw data compared to the arbitrary velocity thresholds (mean difference of 0.030, 95% CI = 0.028 to 0.032, $P < 0.001$, ES = 5.34).

3.3.3 Activity profile

The total distance covered by elite GFR during match play was $9,418 \pm 706$ m. The peak running speed achieved was 6.73 ± 0.51 m·s⁻¹. The distance covered in each movement category is presented in Table [3.1](#). As the number of movement categories generated was equal to the number used previously in the analysis of IFTS, the distance covered in each of the newly generated categories was compared to the corresponding arbitrary movement category. The differences in distance covered between the lowest three categories and highest three categories are presented in Figure [3.4](#) and Figure [3.5](#), respectively. The distance covered was different ($P < 0.001$) in the newly generated very

low-speed movement (VLSM) (ES = 4.72), walking (ES = 3.57), LSR (ES = 2.52), moderate-speed running (MSR) (ES = 3.09), HSR (ES = 2.90) and VHSR (ES = 0.61) categories in comparison to the corresponding arbitrary movement category.

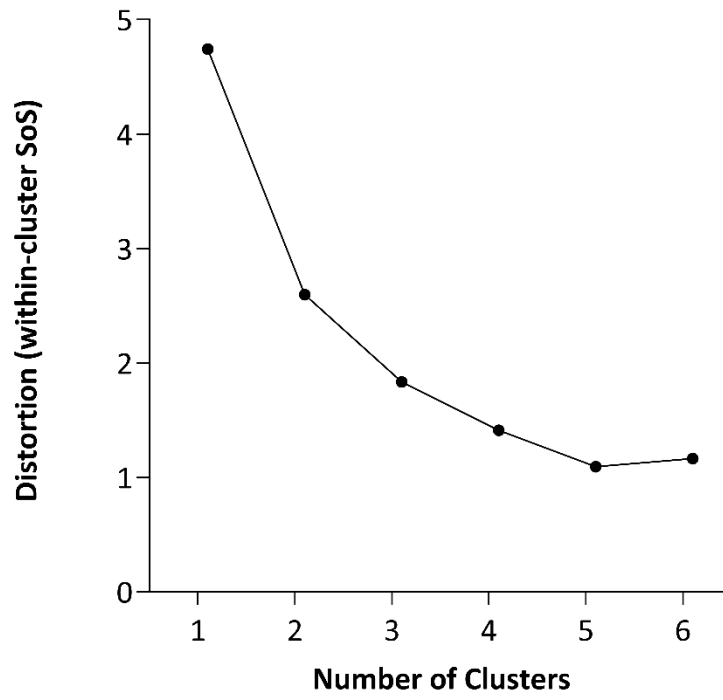


Figure 3.3. Elbow curve formed using the within-cluster sum of squares for each cluster based on the Euclidean distance for each data point from each cluster centroid. SoS, sum of squares.

Table 3.1. Verbal descriptor, velocity thresholds, and distance covered in each movement category

Verbal Descriptor	Velocity Thresholds (m·s⁻¹)	Distance (m)
Very low-speed movement	<0.70	164.1 ± 34.8
Walking	≥0.70 – 1.65	2,026.8 ± 273.8
Low-speed running	≥1.66 – 3.27	2,854.0 ± 395.6
Moderate-speed running	≥3.28 – 4.86	3,407.6 ± 542.3
High-speed running	≥4.87 – 6.48	940.5 ± 375.0
Very high-speed running	≥6.49	25.0 ± 45.5

Velocity thresholds are presented as range. Distance is presented as mean ± SD.

Table 3.2. Regression analysis of the newly generated GFR movement category velocity thresholds versus arbitrary velocity thresholds

	Group 1		Group 2		Group 3	
	Unsupervised Clustering	Arbitrary Thresholds	Unsupervised Clustering	Arbitrary Thresholds	Unsupervised Clustering	Arbitrary Thresholds
Game 1	0.936	0.917	0.929	0.894	0.927	0.893
Game 2	0.908	0.875	0.932	0.905	0.919	0.879
Game 3	0.897	0.860	0.920	0.883	0.933	0.903
Game 4	0.900	0.869	0.923	0.890	0.924	0.890
Game 5	0.933	0.903	0.929	0.894	0.923	0.899
Game 6	0.927	0.888	0.925	0.889	0.924	0.891
Game 7	0.933	0.908	0.936	0.913	0.928	0.900
Game 8	0.908	0.875	0.917	0.888	0.937	0.915
Game 9	0.928	0.904	0.933	0.908	0.939	0.912
Game 10	0.921	0.900	0.925	0.898	0.931	0.904
Mean	0.919	0.890	0.927	0.896	0.929	0.899

Data are presented as adjusted r^2 .

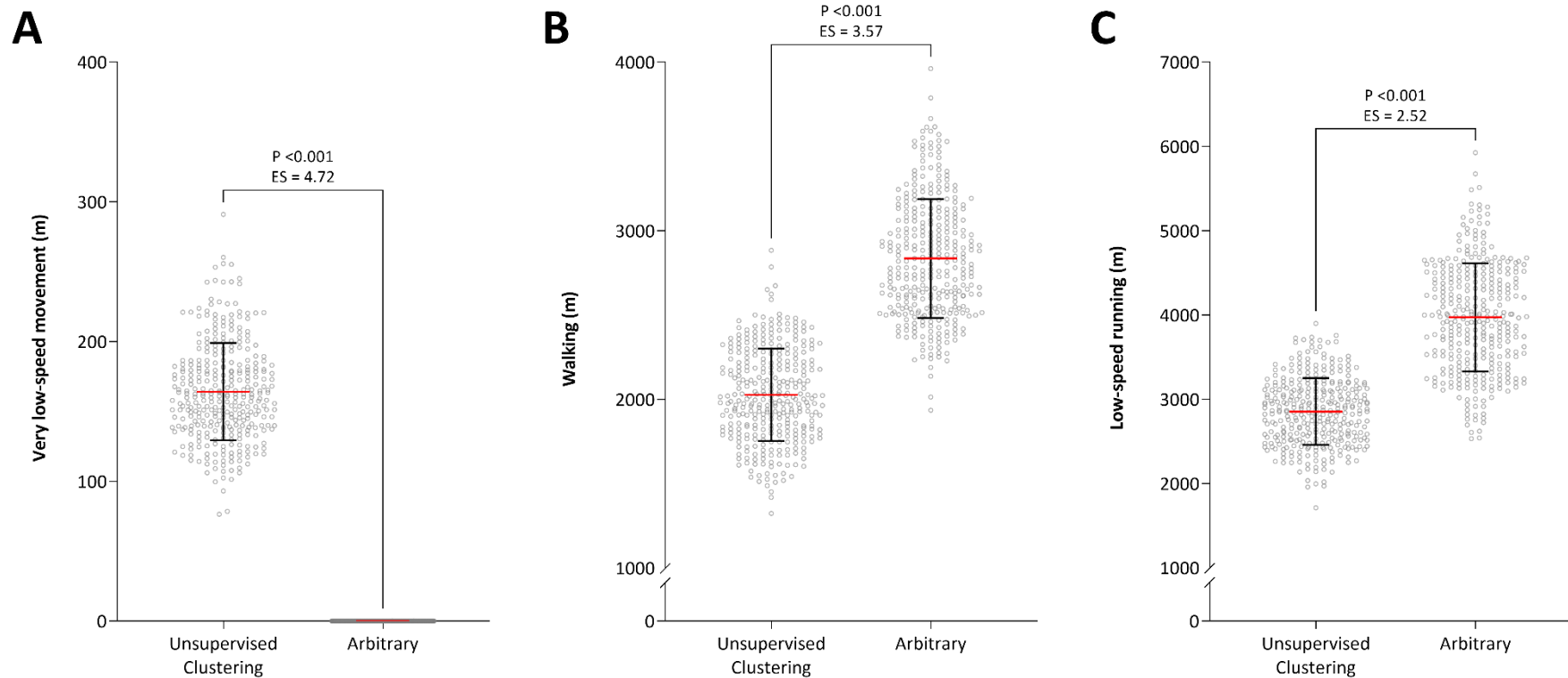


Figure 3.4. Distance covered in the newly generated VLSM (A), Walking (B), and LSR (C) categories compared to the distance covered in the corresponding arbitrary movement category. Data are presented as mean with error bars representing SD and circles representing individual data points.

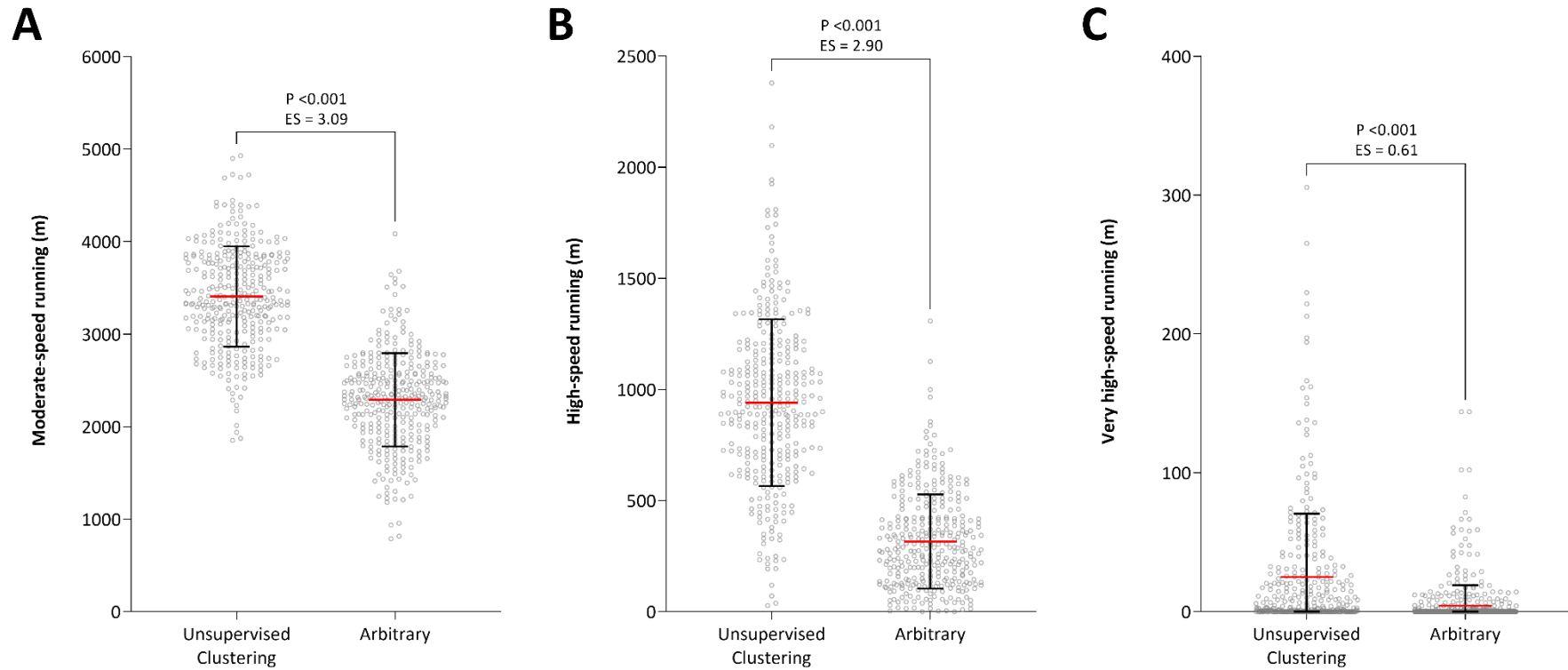


Figure 3.5. Distance covered in the newly generated MSR (A), HSR (B), and VHSR (C) categories compared to the distance covered in the corresponding arbitrary movement category. Data are presented as mean with error bars representing SD and circles representing individual data points.

3.4 Summary

Using a two-stage unsupervised clustering technique, six unique movement categories and their respective velocity thresholds were determined for elite GFR. These thresholds were subsequently compared to arbitrary velocity thresholds that have been frequently used in previous studies analysing IFTS players and referees. The newly generated velocity thresholds demonstrated a stronger relation with the raw velocity data.

Given that the number of movement categories generated for elite GFR was the same as that previously used with IFTS referees, the distance within each category was compared. The distance covered in each of the newly generated movement categories was different compared to the corresponding arbitrary category. In particular, the distance covered in the two highest categories generated for GFR resulted in a 201% increase compared to the distance covered in the two highest arbitrary categories.

CHAPTER IV

STUDY 2

ACTIVITY PROFILE AND TEMPORAL CHANGES OF ELITE GAELIC FOOTBALL REFEREES DURING MATCH PLAY IN THE ALL-IRELAND CHAMPIONSHIP

4.1 Introduction

4.1.1 Rationale

The NFL, contested between January and April, and the AIC, contested between May and September are the two major Gaelic football competitions played annually. The AIC commences each year with the four provincial championships, namely the Connacht, Leinster, Munster and Ulster championships. Games at provincial level are played on a knockout basis with the winners of each province progressing directly to the AIS. The losers of each successive round in the provincial championships enter the AIQ, often referred to as the 'back door', and can progress to the AIS by winning successive qualifying games. To date, no study has examined the activity profile of elite GFR during AIC games. Further, there is no information available on the differences in the activity profile of elite GFR during the AIQ, provincial championships or AIS.

Analysis of the seasonal changes in the activity profile of elite Gaelic football players found a greater total and HSR distance ($\geq 4.72 \text{ m}\cdot\text{s}^{-1}$) during the latter stages of the AIC compared to any other phase of the season (11). The HSR distance during the fourth quarter of games in August and September was also greater than any other phase of the season by 21 – 42%. This increase in HSR distance during the latter stages of the AIC may reflect a greater match intensity in games involving the top eight teams (11). Similar to

elite soccer referees (60), the activity profile of GFR may also vary in response to that of the players. Understanding the activity profile of elite GFR during the different phases of the AIC will assist athletic development coaches in designing conditioning programmes to ensure that they can cope with potential increases in game intensity throughout the AIC.

While full-game match analysis provides a global measure of the activity profile of IFTS players and referees, failure to examine the temporal changes in activity profile may mask decrements in running performance during the latter stages of games. These changes are of particular importance considering that soccer referees have been found to make more errors and to be positioned further from infringements in the attacking areas of the pitch during the latter stages of games (15, 16).

Mixed results have been reported for the temporal changes in the activity profile of soccer and rugby referees (105, 106, 129). A decrement in the total distance covered in the second half was reported for elite Premier League soccer referees but no difference was found between halves for HSR distance ($>5.5 \text{ m}\cdot\text{s}^{-1}$) (106). In contrast, the distance covered while jogging ($2.0 - 4.0 \text{ m}\cdot\text{s}^{-1}$), running ($4.0 - 5.5 \text{ m}\cdot\text{s}^{-1}$) and running at high-speed ($5.5 - 7.0 \text{ m}\cdot\text{s}^{-1}$) was lower during the second half of match play in elite soccer competitions (58). Although there was no difference in the total distance covered between halves in rugby league, the number of high-intensity efforts ($>5.5 \text{ m}\cdot\text{s}^{-1}$) performed by the referee was 14% lower in the second half than the first (129). A reduction in the running performance of elite GFR during the latter stages of games may also indicate an impaired ability to keep up with play and increase the likelihood of incorrect decisions (14). The purpose of this study was therefore to use specifically generated movement category

velocity thresholds to examine the activity profile and temporal changes of elite GFR during match play in all phases of the AIC.

4.1.2 Study aims

1. To examine the activity profile of elite GFR during AIC games
2. To compare the temporal changes in the activity profile of elite GFR between the first and second half and between the four quarters of AIC games
3. To compare the activity profile of elite GFR during the AIQ, provincial championships and AIS
4. To compare the temporal changes in activity profile of elite GFR between the first and second half and between the four quarters of the AIQ, provincial championships and AIS

4.1.3 Study hypotheses

1. The majority of the total distance covered during AIC games will be completed at low and moderate speeds
2. During AIC games, there will be a significant decrease in the total and HSR distance and peak running speed between the first and second halves and in the fourth quarter compared to any other quarter
3. There will be significantly more total and HSR distance covered during the AIS and provincial championships than in the AIQ
4. There will be a significant decrease in the total and HSR distance and peak running speed between the first and second half of the AIQ, provincial championships and AIS, and in the fourth quarter of the AIQ but not in the provincial championships or AIS

4.2 Methodology

4.2.1 Overview of study design

A longitudinal observational study design was used to evaluate the activity profile of elite GFR during games played in the AIC from 2016 to 2019. Participants were members of the elite panel of referees selected prior to the start of the AIC each year. Match activity data were collected during 80% of AIC games comprising all phases of the competition including semi-finals and finals using GPS and GNSS technology. The activity data were used to quantify the distances and running speeds achieved by GFR during AIC games and during the three phases of the AIC. The data were also separated into halves and quarters to examine temporal changes during match play.

4.2.2 Participants

Twenty-three elite inter-county GFR (mean \pm SD; age: 39.5 ± 4.7 years; height: 173.7 ± 5.8 cm; weight: 78.0 ± 6.9 kg; BMI: 25.9 ± 2.0 kg·m²) provided written informed consent to participate in the study. Referees included in the study had a median (range) of 7.0 (0.0 – 18.9) years' experience officiating at national level and 4.6 (0.0 – 14.8) years officiating in the AIC. Ethical approval was obtained from Dublin City University Research Ethics Committee (Appendix [1](#)) in accordance with the Declaration of Helsinki.

4.2.3 Anthropometry

As described in Chapter 3, Section [3.2.3](#)

4.2.4 Data collection

A total of 206 AIC full game data files were collected from 2016 to 2019. Data files were collected as described in Chapter 3, Section [3.2.4](#)

4.2.5 Data processing

Data files were processed as described in Chapter 3, Section [3.2.5](#). This approach resulted in the exclusion of one data file. Four data files were also identified as outliers based on match duration and were excluded from further analysis. This resulted in a final dataset of 201 full game data files, with a median of 9 full game data files per referee (mean = 8.7 games; range: 2 – 19 games). A breakdown of the data files collected during each phase of the AIC is presented in [Figure 4.1](#).

4.2.6 Movement variables

The movement variables analysed were total distance, VLSM ($<0.70 \text{ m}\cdot\text{s}^{-1}$), walking ($\geq 0.70 - 1.65 \text{ m}\cdot\text{s}^{-1}$), LSR ($\geq 1.66 - 3.27 \text{ m}\cdot\text{s}^{-1}$), MSR ($\geq 3.28 - 4.86 \text{ m}\cdot\text{s}^{-1}$), HSR ($\geq 4.87 - 6.48 \text{ m}\cdot\text{s}^{-1}$), VHSR ($\geq 6.49 \text{ m}\cdot\text{s}^{-1}$) and peak running speed. These categories were derived from the unsupervised clustering technique in Chapter 3, Study 1. The total distance and distance covered within each movement category was calculated using the instantaneous velocity and time at each observation. To account for differences in duration between games, the total distance and distance covered in each movement category was reported in relative terms, expressed as metres and distance per unit time ($\text{m}\cdot\text{min}^{-1}$). Expressing the data in relative terms also enabled the additional time at the end of each half to be included. To examine the temporal changes in the activity profile, full game data files were

separated into the first and second half and into four quarters representing the first and last fifteen minute periods in each half.

4.2.7 Statistical analysis

Statistical analysis was completed using SPSS (v.25) (IBM, Chicago, IL, USA). Data are presented as mean \pm SD, unless otherwise stated. Temporal changes in the movement variables during AIC games, and between the AIQ, provincial championships and AIS were examined using a series of linear mixed models (LMM). Match period was treated as a repeated measure with competition phase, playing season, and a match period and competition phase interaction included as fixed effects. Match period included the four match quarters and the period between the two quarters within each half. Competition phase included the three phases of the AIC and the four divisions of the NFL. Referee and a referee and match period interaction were treated as random effects. The utility of referee as a random effect was examined for each movement variable using a null model. The null model contained no fixed effect and only referee as a random effect. The ICC was subsequently determined using the between-referee (residual) variance component and the sum of the within-referee and between-referee variance components. If the ICC was <0.5 the random effect of referee would have been removed from the LMM (157). The ICC for each movement variable is presented in Table [4.1](#).

The covariance structure of the repeated measure for each LMM was determined according to the Akaike Information Criterion. For relative distance and distance in each movement category, a compound symmetry heterogeneous structure was fitted. An unstructured covariance structure was fitted for peak running speed. After determination

of the appropriate covariance structure, normality assumptions of the residuals were examined using plots of the model residuals and the predicted values. Where the assumptions were violated, the dependant variable was log transformed. Significant main effects and interactions were probed using Bonferroni adjusted contrasts. Estimates of ES were calculated according to Westfall, Judd and Kenny (158) which provides an estimate analogous to Cohen's *d*. This approach is recommended for LMM designs (159). The significance level was set at $\alpha \leq 0.05$ for all tests.

Table 4.1. Intraclass correlation coefficient for each movement variable

	Referee	Residual	ICC
RD (m·min ⁻¹)	42.126	169.305	0.80
VLSM (m·min ⁻¹)	0.002	0.006	0.79
Walking (m·min ⁻¹)	10.786	11.674	0.52
LSR (m·min ⁻¹)	21.343	35.222	0.62
MSR (m·min ⁻¹)	24.309	87.368	0.78
HSR (m·min ⁻¹)	0.022	0.053	0.71
VHSR (m·min ⁻¹)	0.013	0.020	0.60
Peak running speed (m·s ⁻¹)	0.129	0.165	0.56

ICC, intraclass correlation coefficient; RD, relative distance; VLSM, very low-speed movement, LSR, low-speed running; MSR, moderate-speed running; HSR, high-speed running; VHSR, very high-speed running.

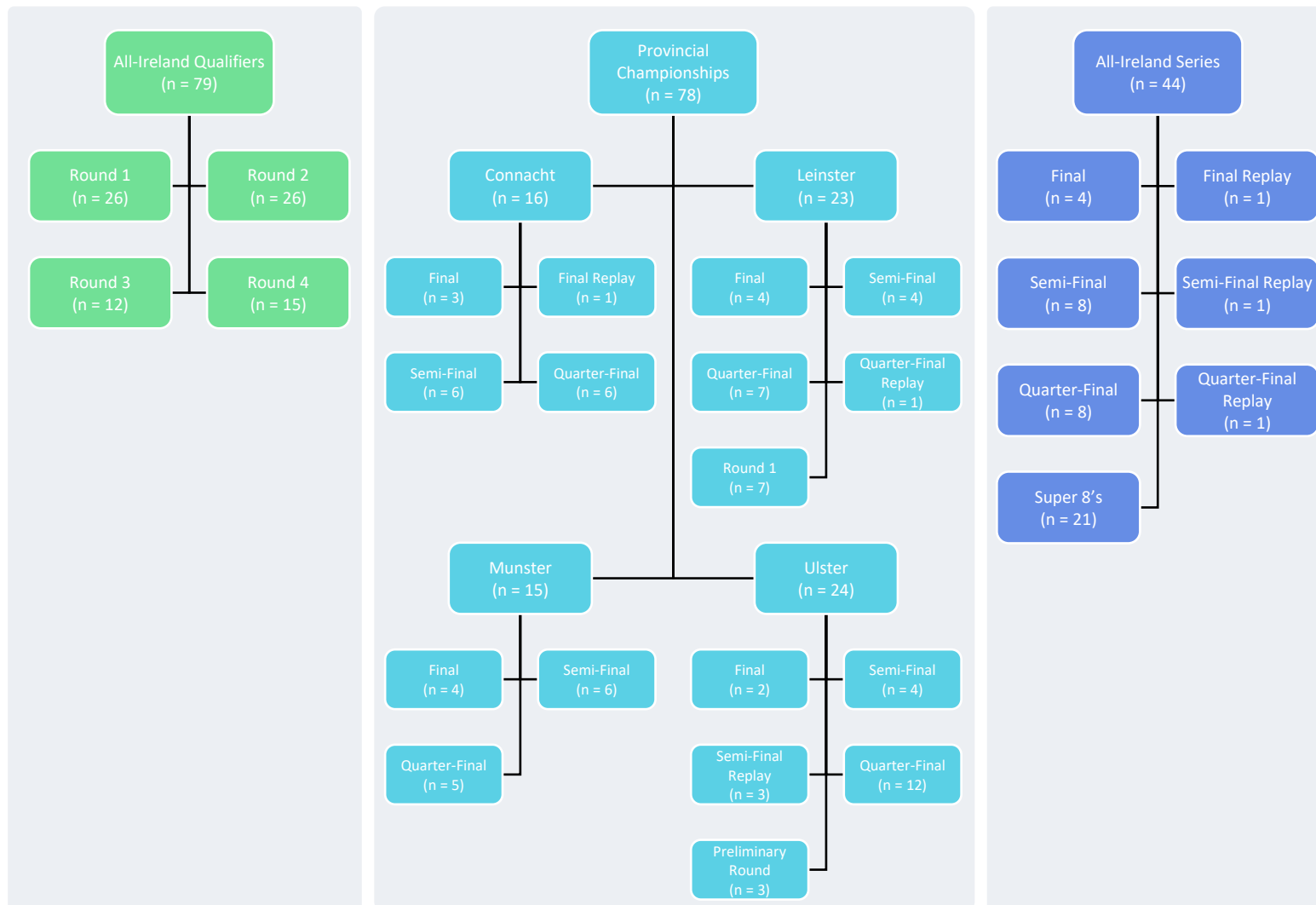


Figure 4.1. Breakdown of data files collected from games in each round and phase of the AIC.

4.3 Results

4.3.1 Activity profile during the AIC

4.3.1.1 Full game

The mean game duration and relative distance during the AIC was 78.0 ± 2.3 min and 122.6 ± 8.4 m·min⁻¹, respectively. During the full game, referees completed 2.1 ± 0.4 m·min⁻¹ of VLSM, 26.1 ± 3.3 m·min⁻¹ of walking, 36.8 ± 4.9 m·min⁻¹ of LSR, 44.5 ± 6.6 m·min⁻¹ of MSR, 12.8 ± 4.7 m·min⁻¹ of HSR and 0.3 ± 0.5 m·min⁻¹ of VHSR. The peak running speed was 6.75 ± 0.49 m·s⁻¹.

4.3.1.2 Comparisons between the first and second half

The duration of the first and second half was 37.7 ± 1.3 min and 40.3 ± 1.8 min ($P < 0.001$, ES = 1.92), respectively. The relative distance during the first and second half was 126.8 ± 8.8 m·min⁻¹ and 118.8 ± 9.6 m·min⁻¹ ($P < 0.001$, ES = -0.60), respectively. The relative distance in each movement category during the first and second half is presented in Table 4.2. The relative distance involving VLSM and walking was lower ($P < 0.001$) in the first half than the second half, while the relative distance in the LSR, MSR and HSR categories was higher ($P < 0.01$) in the first half than the second half. There was no difference in peak running speed ($P = 0.388$, ES = 0.07) between the first (6.54 ± 0.49 m·s⁻¹) and second half (6.61 ± 0.48 m·s⁻¹).

4.3.1.3 Comparisons across the four match quarters

The relative distance was significantly different across the quarters of match play. A greater relative distance was covered during the first quarter (132.8 ± 10.9 m·min⁻¹) than

the second ($121.9 \pm 11.6 \text{ m}\cdot\text{min}^{-1}$, $P < 0.001$, $ES = -0.82$), third ($120.2 \pm 12.5 \text{ m}\cdot\text{min}^{-1}$, $P < 0.001$, $ES = -0.91$) and fourth quarters ($118.1 \pm 13.3 \text{ m}\cdot\text{min}^{-1}$, $P < 0.001$, $ES = -1.12$), respectively. The relative distance in the second quarter was also higher ($P = 0.002$, $ES = -0.30$) than the fourth quarter. The relative distance in each movement category during each quarter and between the four quarters is presented in Table [4.3](#). The relative distance involving VLSDM was lower ($P < 0.001$) in the first and second quarters than the third and fourth quarters. The relative distance in the walking and LSR categories was lower in the first quarter ($P < 0.001$) compared to any other match period, while the relative distance in the MSR and HSR categories was higher ($P < 0.001$) in the first quarter than in any other match period. The relative distance in the LSR category during the fourth quarter was also lower ($P < 0.001$) compared to any other match period. The ES with 95% confidence intervals (CI) for the relative distance in each movement category between the four quarters is presented in Figure [4.2](#). No significant differences in the peak running speed were observed between the quarters of match play ($ES = -0.12$ to 0.10).

Table 4.2. Relative distance in each movement category during the first and second half of match play during the AIC

	Match Period		P value	ES (95% CI)
	First Half	Second Half		
VLSM (m·min ⁻¹)	1.9 ± 0.4	2.2 ± 0.5	<0.001	0.06 (-0.13 to 0.26)
Walking (m·min ⁻¹)	25.7 ± 3.6	26.6 ± 3.5	<0.001	0.23 (0.03 to 0.42)
LSR (m·min ⁻¹)	38.4 ± 5.4	35.2 ± 5.2	<0.001	-0.45 (-0.65 to -0.25)
MSR (m·min ⁻¹)	47.1 ± 7.4	42.2 ± 7.0	<0.001	-0.50 (-0.70 to -0.30)
HSR (m·min ⁻¹)	13.4 ± 5.3	12.3 ± 5.0	0.010	-0.14 (-0.34 to -0.05)
VHSR (m·min ⁻¹)	0.3 ± 0.7	0.3 ± 0.5	0.137	0.08 (-0.12 to 0.28)
HSR+VHSR (m·min ⁻¹)	13.7 ± 5.5	12.6 ± 5.2	0.016	-0.13 (-0.33 to 0.06)

Data are presented as mean ± SD. ES, effect size; VLSM, very low-speed movement; LSR, low-speed running; MSR, moderate-speed running; HSR, high-speed running; VHSR, very high-speed running.

Table 4.3. Relative distance in each movement category across the four quarters of match play during the AIC

	Match Period			
	First Quarter	Second Quarter	Third Quarter	Fourth Quarter
VLSM (m·min ⁻¹)	1.9 ± 0.5	2.0 ± 0.6	2.1 ± 0.6 ^{a,b}	2.2 ± 0.7 ^{a,b}
Walking (m·min ⁻¹)	24.2 ± 3.9	27.1 ± 4.1 ^a	25.5 ± 4.2 ^{a,b}	27.2 ± 4.2 ^{a,c}
LSR (m·min ⁻¹)	40.2 ± 6.0	36.9 ± 6.4 ^a	36.1 ± 6.3 ^a	34.8 ± 6.4 ^{a,b,d}
MSR (m·min ⁻¹)	51.0 ± 9.4	43.6 ± 8.7 ^a	43.6 ± 8.9 ^a	41.3 ± 9.0 ^{a,d}
HSR (m·min ⁻¹)	15.2 ± 7.1	12.1 ± 5.7 ^a	12.5 ± 6.0 ^a	12.3 ± 6.7 ^a
VHSR (m·min ⁻¹)	0.3 ± 0.9	0.3 ± 1.0	0.3 ± 0.7	0.4 ± 0.9
HSR+VHSR (m·min ⁻¹)	15.5 ± 7.5	12.4 ± 6.1 ^a	12.8 ± 6.3 ^a	12.6 ± 6.9 ^a

Data are presented as mean ± SD. ^a P <0.001 vs. First Quarter; ^b P <0.001 vs. Second Quarter; ^c P <0.001 vs. Third Quarter; ^d P <0.01 vs. Third Quarter. VLSM, very low-speed movement; LSR, low-speed running; MSR, moderate-speed running; HSR, high-speed running; VHSR, very high-speed running.

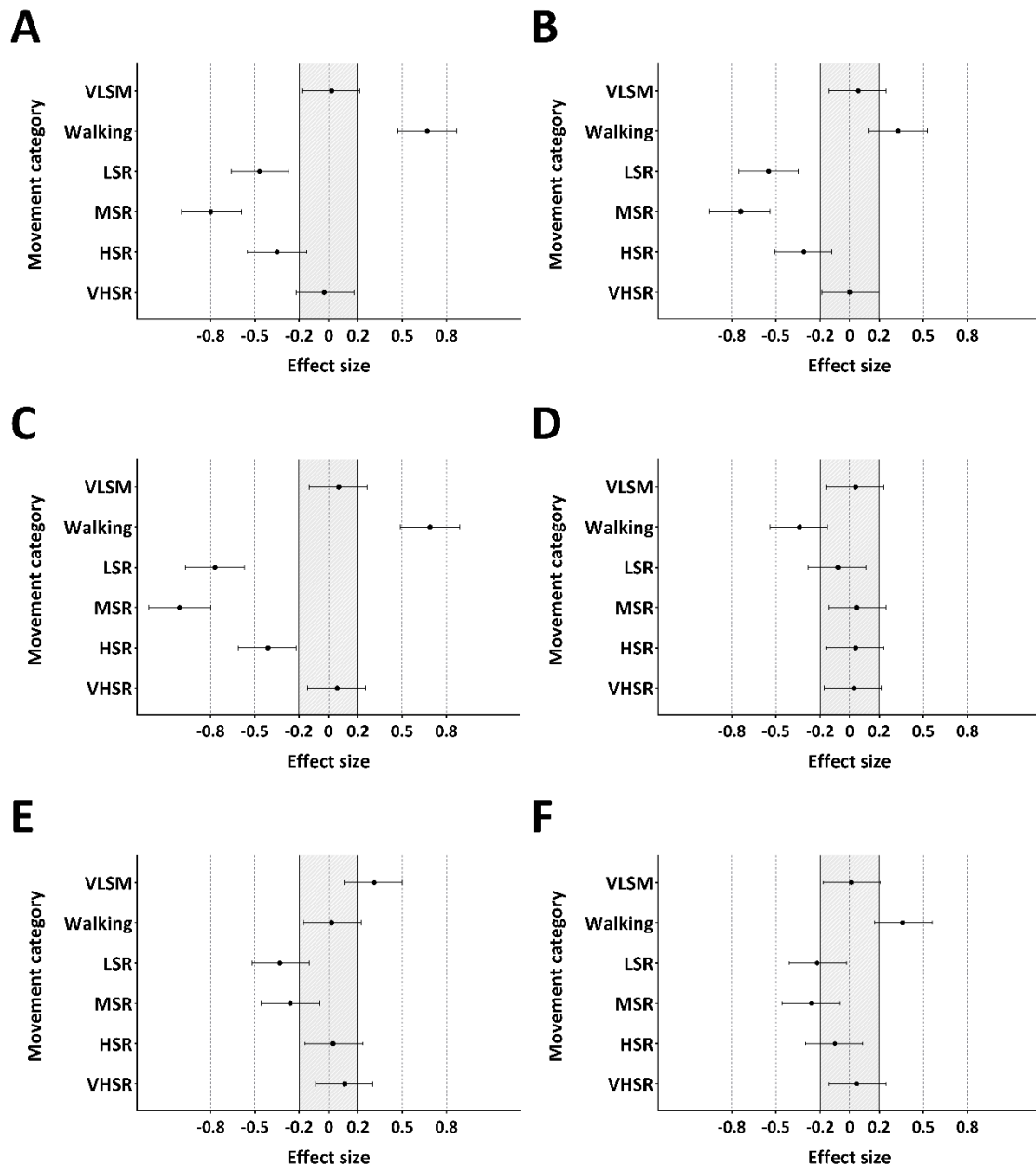


Figure 4.2. Effect size plots of the change in relative distance in each movement category from the first to second (A), first to third (B), first to fourth (C), second to third (D), second to fourth (E), and third to fourth (F) quarter of the AIC. Circles represent the ES and the horizontal lines represent the 95% confidence interval. VLSM, very low-speed movement; LSR, low-speed running; MSR, moderate-speed running; HSR, high-speed running; VHSR, very high-speed running.

4.3.2 AIC phase comparisons

4.3.2.1 Full game

The mean game duration during the AIQ, provincial championships and AIS was 78.0 ± 2.1 min, 77.3 ± 2.2 min and 79.1 ± 2.5 min, during which referees covered a relative distance of 122.4 ± 8.0 m·min⁻¹, 123.3 ± 9.2 m·min⁻¹ and 121.6 ± 7.6 m·min⁻¹, respectively. The mean game duration during the AIS was higher than the provincial championships ($P < 0.001$, ES = 0.55). There were no differences in relative distance between the three phases of the AIC (ES = 0.04 to 0.18). The relative distance in each movement category across the full game for each of the three phases of the AIC is presented in Table 4.4. Only LSR differed between phases, with higher values in the AIS than both the provincial championships ($P = 0.016$, ES = -0.21) and the AIQ ($P = 0.012$, ES = -0.22). The peak running speed was higher during the AIS (6.93 ± 0.52 m·s⁻¹) than the AIQ (6.65 ± 0.46 m·s⁻¹, $P = 0.010$, ES = -0.33). There was no difference in peak running speed between the provincial championships (6.74 ± 0.48 m·s⁻¹) and the AIQ ($P = 0.233$, ES = -0.12) or the AIS ($P = 0.085$, ES = 0.21).

4.3.2.2 Comparisons between the first and second half

The relative distance during the first half was 127.0 ± 8.5 m·min⁻¹, 127.2 ± 9.8 m·min⁻¹ and 125.5 ± 7.3 m·min⁻¹ in the AIQ, provincial championships and AIS, respectively. The relative distance during the second half was 118.3 ± 9.7 m·min⁻¹, 119.7 ± 9.8 m·min⁻¹ and 118.0 ± 9.1 m·min⁻¹ in the AIQ, provincial championships and AIS, respectively. The relative distance was higher in the first half than the second half of the AIQ ($P < 0.001$, ES = -0.64), the provincial championships ($P < 0.001$, ES = -0.58) and the AIS ($P < 0.001$, ES = -

0.58). There was no significant difference in relative distance for the first half (ES = -0.15 to 0.11) or second half (ES = -0.16 to 0.21) between the three AIC phases. The relative distance in each movement category during the first and second half in the three AIC phases is presented in Table [4.5](#). The relative distance in the VLSM and walking categories was lower ($P < 0.01$) in the first half than the second half for all three phases of the AIC, while the relative distance in the LSR and MSR categories was higher ($P < 0.001$) in the first half than the second half for all three phases of the AIC. The only between phase difference was in the LSR category, which was lower ($P < 0.01$) in the second half of the AIQ than the AIS. There was no significant difference in the relative distance in the HSR or VHSR categories or in peak running speed between halves and between the three phases of the AIC.

4.3.2.3 Comparisons across the four match quarters

The differences in relative distance across the four quarters of match play for each of the three phases of the AIC are presented in Figure [4.3](#). For all phases, the relative distance in the first quarter was greater ($P < 0.001$) than any other match period. The relative distance in the second quarter of the AIQ and third quarter of the AIS was also higher than the respective fourth quarter. The relative distance in each movement category during each quarter and between the quarters for each of the three phases of the AIC is presented in Table [4.6](#).

The relative distance involving VLSM was lower ($P < 0.01$) in the first and second quarters than the third and fourth quarters in the AIQ and provincial championships but was only lower ($P < 0.001$) than the fourth quarter of the AIS. For all phases of the AIC,

relative distance involving walking and LSR was lower ($P < 0.01$) in the first quarter than any other match period, while MSR was higher ($P < 0.001$) than any other match period. The relative distance in the LSR category was lower ($P < 0.01$) in the fourth quarter than the second quarter of the AIQ and any other match period in the AIS. The relative distance involving MSR was lower ($P < 0.01$) than any other period in the AIQ. The relative distance involving HSR was higher ($P < 0.01$) in the first quarter than the third and fourth quarters of the AIQ and higher ($P < 0.01$) in the first quarter than any other match period of the provincial championships. In the AIS, the relative distance in the HSR category was higher ($P < 0.01$) in the first quarter than the fourth quarter. There were no differences in the relative distance in any movement category during the four quarters between the three phases of the AIC. There were also no differences in the relative distance in the VHRSR category or peak running speed across quarters during any of the three phases of the AIC.

Table 4.4. Relative distance in each movement category during the full game in the three phases of the AIC

	All-Ireland Qualifiers	Provincial	All-Ireland Series
VLSM (m·min ⁻¹)	2.0 ± 0.4	2.1 ± 0.4	2.1 ± 0.4
Walking (m·min ⁻¹)	26.2 ± 3.2	26.0 ± 3.4	26.3 ± 3.6
LSR (m·min ⁻¹)	36.6 ± 5.5	36.4 ± 4.9	37.7 ± 4.3 ^a
MSR (m·min ⁻¹)	44.9 ± 6.1	45.2 ± 7.3	42.7 ± 6.1
HSR (m·min ⁻¹)	12.5 ± 4.4	13.3 ± 5.1	12.3 ± 4.2
VHSR (m·min ⁻¹)	0.2 ± 0.5	0.3 ± 0.6	0.4 ± 0.5
HSR+VHSR (m·min ⁻¹)	12.7 ± 4.6	13.7 ± 5.4	12.7 ± 4.4

Data are presented as mean ± SD. ^a P <0.05 vs. All other phases. VLSM, very low-speed movement; LSR, low-speed running; MSR, moderate-speed running; HSR, high-speed running; VHSR, very-high speed running.

Table 4.5. Relative distance in each movement category during the first and second half and between the three phases of the AIC

	Championship Phase	Match Period	
		First Half	Second Half
VLSM (m·min ⁻¹)	All-Ireland Qualifiers	1.9 ± 0.4	2.1 ± 0.5 ^a
	Provincial	1.9 ± 0.5	2.2 ± 0.5 ^a
	All-Ireland Series	2.0 ± 0.4	2.3 ± 0.5 ^a
Walking (m·min ⁻¹)	All-Ireland Qualifiers	25.7 ± 3.5	26.7 ± 3.4 ^a
	Provincial	25.5 ± 3.6	26.4 ± 3.6 ^a
	All-Ireland Series	25.9 ± 3.9	26.6 ± 3.7 ^b
LSR (m·min ⁻¹)	All-Ireland Qualifiers	38.6 ± 5.8	34.8 ± 5.2 ^{a,†}
	Provincial	37.8 ± 5.6	35.1 ± 5.0 ^a
	All-Ireland Series	39.3 ± 4.1	36.3 ± 5.3 ^a
MSR (m·min ⁻¹)	All-Ireland Qualifiers	47.6 ± 7.0	42.5 ± 6.5 ^a
	Provincial	47.8 ± 8.0	42.7 ± 7.7 ^a
	All-Ireland Series	44.7 ± 6.3	40.8 ± 6.6 ^a
HSR (m·min ⁻¹)	All-Ireland Qualifiers	13.0 ± 5.2	12.0 ± 4.7
	Provincial	13.9 ± 5.7	12.9 ± 5.4
	All-Ireland Series	13.2 ± 4.8	11.6 ± 4.5
VHSR (m·min ⁻¹)	All-Ireland Qualifiers	0.2 ± 0.6	0.3 ± 0.5
	Provincial	0.3 ± 0.8	0.3 ± 0.5
	All-Ireland Series	0.4 ± 0.6	0.4 ± 0.6
HSR+VHSR (m·min ⁻¹)	All-Ireland Qualifiers	13.2 ± 5.4	12.3 ± 4.9
	Provincial	14.2 ± 6.0	13.2 ± 5.6
	All-Ireland Series	13.6 ± 4.9	12.0 ± 4.8

Data are presented as mean ± SD. ^a P <0.001 vs. First Half; ^b P <0.01 vs. First Half, [†] P <0.01 vs. All-Ireland Series. VLSM, very low-speed movement; LSR, low-speed running; MSR, moderate-speed running; HSR, high-speed running; VHSR, very high-speed running.

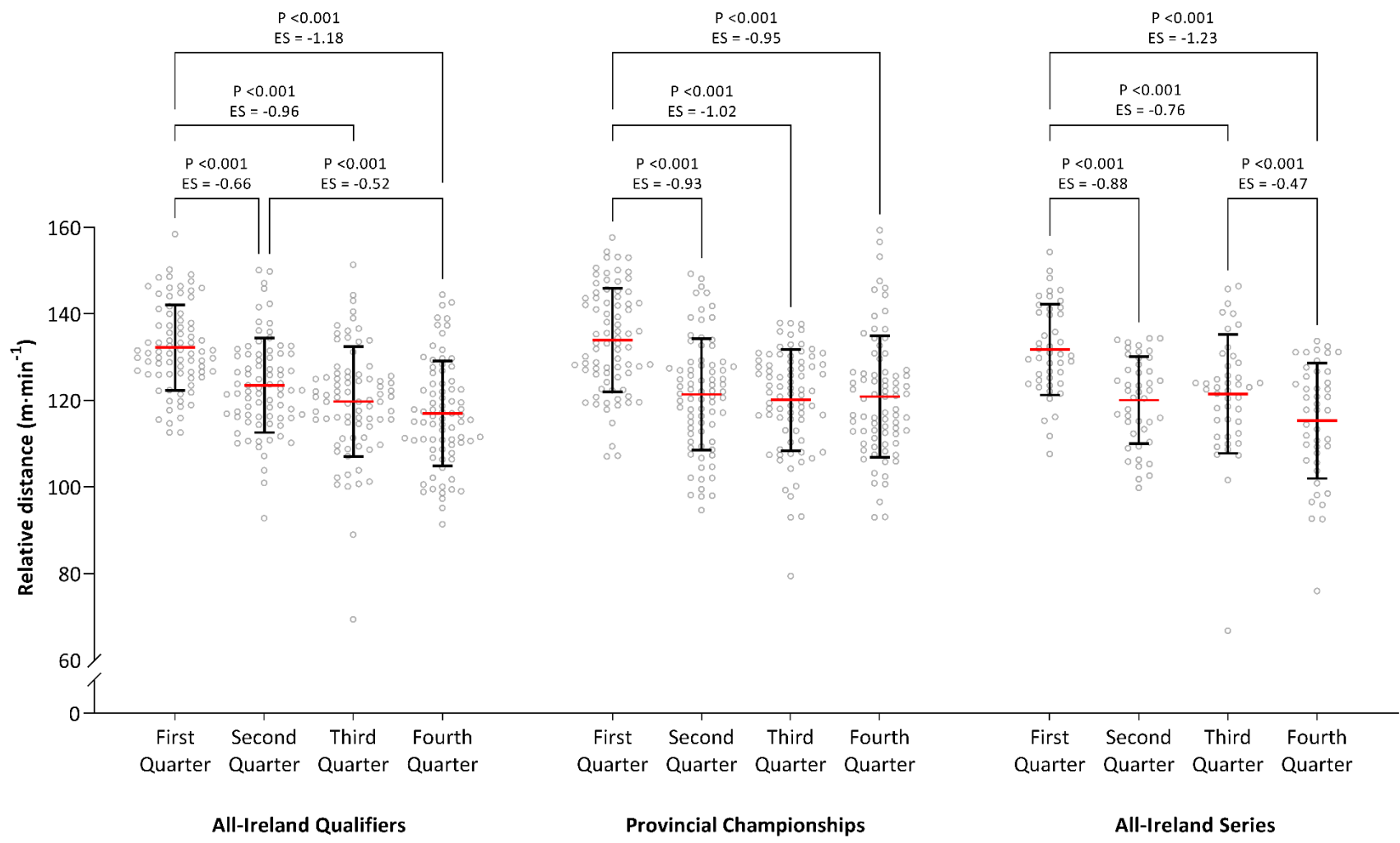


Figure 4.3. Relative distance across each quarter of match play for the All-Ireland Qualifiers, provincial championships, and All-Ireland Series. Data are presented as mean with error bars representing SD and circles representing individual data points.

Table 4.6. Relative distance in each movement category across the four quarters of match play between the three phases of the AIC

	Championship Phase	Match Period			
		First Quarter	Second Quarter	Third Quarter	Fourth Quarter
VLSM (m·min ⁻¹)	All-Ireland Qualifiers	1.8 ± 0.4	1.9 ± 0.5	2.1 ± 0.6 ^{a,d}	2.1 ± 0.6 ^{a,d}
	Provincial	1.9 ± 0.5	2.0 ± 0.6	2.1 ± 0.6 ^a	2.1 ± 0.6 ^c
	All-Ireland Series	2.0 ± 0.5	2.0 ± 0.6	2.2 ± 0.5	2.4 ± 0.8 ^{a,b}
Walking (m·min ⁻¹)	All-Ireland Qualifiers	24.6 ± 3.8	26.8 ± 4.1 ^a	25.9 ± 4.0 ^c	27.3 ± 4.2 ^{a,e}
	Provincial	24.0 ± 3.9	26.9 ± 4.1 ^a	25.3 ± 4.2 ^{c,d}	27.1 ± 4.3 ^{a,e}
	All-Ireland Series	24.0 ± 4.0	27.9 ± 4.2 ^a	25.3 ± 4.5 ^{b,c}	27.4 ± 4.1 ^{a,e}
LSR (m·min ⁻¹)	All-Ireland Qualifiers	40.8 ± 6.7	36.9 ± 6.1 ^a	35.9 ± 6.6 ^a	34.6 ± 6.6 ^{a,d}
	Provincial	39.3 ± 5.9	36.3 ± 6.5 ^a	35.4 ± 5.9 ^a	35.3 ± 6.4 ^a
	All-Ireland Series	40.7 ± 4.8	37.9 ± 6.7 ^c	37.7 ± 6.4 ^c	34.4 ± 6.1 ^{a,d,e}
MSR (m·min ⁻¹)	All-Ireland Qualifiers	50.6 ± 9.0	45.5 ± 8.5 ^a	43.8 ± 8.8 ^a	40.7 ± 7.7 ^{a,b,e}
	Provincial	52.2 ± 9.9	43.8 ± 9.6 ^a	43.9 ± 9.2 ^a	43.1 ± 9.7 ^a
	All-Ireland Series	49.5 ± 8.9	39.9 ± 6.3 ^a	42.8 ± 8.6 ^a	39.1 ± 9.3 ^a
HSR (m·min ⁻¹)	All-Ireland Qualifiers	14.1 ± 6.7	12.2 ± 5.7	11.7 ± 5.3 ^c	12.0 ± 6.3 ^c
	Provincial	16.3 ± 7.5	12.0 ± 6.2 ^a	13.0 ± 5.8 ^c	13.1 ± 7.4 ^a
	All-Ireland Series	15.1 ± 7.2	11.9 ± 4.9	13.1 ± 7.4	11.4 ± 5.9 ^c
VHSR (m·min ⁻¹)	All-Ireland Qualifiers	0.2 ± 0.8	0.2 ± 0.07	0.2 ± 0.6	0.4 ± 0.9
	Provincial	0.4 ± 0.9	0.4 ± 1.3	0.3 ± 0.7	0.3 ± 0.7
	All-Ireland Series	0.4 ± 0.9	0.4 ± 0.9	0.4 ± 0.7	0.5 ± 1.1
HSR+VHSR (m·min ⁻¹)	All-Ireland Qualifiers	14.3 ± 7.0	12.5 ± 6.0	11.9 ± 5.5 ^c	12.3 ± 6.6 ^c
	Provincial	16.6 ± 7.9	12.4 ± 6.8 ^a	13.3 ± 6.1 ^c	13.4 ± 7.6 ^c
	All-Ireland Series	15.6 ± 7.5	12.3 ± 5.1	13.5 ± 7.7	11.9 ± 6.1 ^c

Data are presented as mean ± SD. ^a P <0.001 vs. First Quarter; ^b P <0.001 vs. Second Quarter; ^c P <0.01 vs. First Quarter; ^d P <0.01 vs. Second Quarter; ^e P <0.01 vs. Third Quarter. VLSM, very low-speed movement; LSR, low-speed running; MSR, moderate-speed running; HSR, high-speed running; VHSR, very high-speed running.

4.4 Summary

The relative distance covered by the referee during AIC games was 122.6 m·min⁻¹. Most of this distance was covered at low and moderate speeds with only 11% covered at high and very high-speed. The relative distance and distance covered within each movement category except VHSR was different between the first and second half of AIC games. There was a higher relative, MSR and HSR distance and a lower walking and LSR distance in the first quarter than any other match period. No differences in HSR, VHSR or peak running speed were found between the second, third and fourth quarters of AIC games.

There was no difference in the relative, HSR or VHSR distance between the three phases of the AIC. Peak running speed was higher during the AIS than the AIQ. For all phases, the relative distance was lower during the second half than the first half but there was no between half difference in HSR, VHSR or peak running speed. The relative distance during the first quarter was greater than any other period in each phase of the AIC. Walking and LSR distance was lower in the first quarter than any other match period during the three phases of the AIC. A greater HSR distance was covered during the first quarter of the provincial championships than any other match period, but HSR distance was only lower during the third and fourth quarter of the AIQ and the fourth quarter of the AIS compared to the first quarter. The relative distance and distance covered within each movement category across the four quarters of match play was similar between all three phases of the AIC.

CHAPTER V

STUDY 3

ACTIVITY PROFILE AND TEMPORAL CHANGES OF ELITE GAELIC FOOTBALL REFEREES DURING MATCH PLAY IN THE NATIONAL FOOTBALL LEAGUE

5.1 Introduction

5.1.1 Rationale

The NFL precedes the AIC each year, with teams competing in a round robin format across four divisions, divided based on ranking. In this format, all teams play each other on one occasion to earn points based on their number of wins, draws and losses. In the NFL, final points totals determine which teams contest the Division 1 finals and compete for promotion and relegation in the lower tiers. Prior to the start of the NFL, a panel of national match officials are selected from each county and province, similar to the selection of players for each inter-county team. In contrast to the AIC referee panel, the NFL referee panel can include referees with no experience at national level. In this regard, the NFL is often used as an opportunity to incorporate new referees from the sub-elite level into the national competitions.

Results from studies examining the influence of team ranking on the activity profile of elite Gaelic football players during competitive match play have been mixed (10, 12). Using the Elo-rating system, higher ranked Gaelic football teams were found to complete more total and HSR distance ($\geq 4.72 \text{ m}\cdot\text{s}^{-1}$) compared to lower ranked teams. The quality of opposition also influenced the activity profile of elite players with top ranked teams completing greater amounts of total and HSR distance ($\geq 4.72 \text{ m}\cdot\text{s}^{-1}$) when competing

against teams of a similar rank compared to low ranking teams (10). In contrast, high-speed activity of a Division 3 team was found to be 11 – 19% higher than a Division 1 team (12). Despite the small sample size and different rating systems between the studies, the differences observed in the activity profile of elite players between divisions and across rankings may impact the activity profile of elite GFR. In soccer, the HR and RPE of elite English referees were 3 – 12% higher when officiating games in the first division compared to the lower divisions (110). Similarly, elite Spanish referees were found to complete a greater number of high-intensity accelerations and decelerations when officiating games involving top ranked teams (141). To date, no studies have examined the impact of division status on the activity profile of elite GFR. The purpose of this study was therefore to use specifically generated velocity thresholds to examine the activity profile and temporal changes of elite GFR during match play in all four divisions of the NFL.

5.1.2 Study aims

1. To examine the activity profile of elite GFR during NFL games
2. To compare the temporal changes in the activity profile of elite GFR between the first and second half and between the four quarters of NFL games
3. To compare the activity profile of elite GFR referees between the four divisions of the NFL
4. To compare the temporal changes in activity profile of elite GFR between the first and second half and between the four quarters of the four divisions of the NFL

5.1.3 Study hypothesis

1. The majority of the total distance covered during NFL games will be completed at low and moderate speeds
2. There will be a significant decrease in the total and HSR distance and peak running speed between the first and second half and in the fourth quarter compared to any other quarter during NFL games
3. There will be significantly more total and HSR distance covered during games in Division 1 than any other division in the NFL
4. There will be a significant decrease in total and HSR distance and peak running speed between the first and second half and in the fourth quarter compared to any other quarter in all four divisions of the NFL

5.2 Methodology

5.2.1 Overview of study design

A longitudinal observational study design was used to evaluate the activity profile of elite GFR during games played in the NFL from 2018 to 2019. Participants were members of the elite panel of referees selected prior to the start of the NFL each year. Match activity data were collected from 57% of NFL games comprising games from each round in all four divisions using GNSS technology. The activity data were used to quantify the distances and running speeds achieved by GFR during NFL games, and in each of the four divisions of the NFL. The data were also separated into halves and quarters to examine temporal changes during match play.

5.2.2 Participants

Thirty-nine elite inter-county GFR (mean \pm SD; age: 38.3 ± 5.5 years; height; 175.9 ± 6.4 cm; weight, 80.0 ± 9.0 kg; BMI, 25.8 ± 2.0 kg·m²) provided written informed consent to participate in the study. Referees included in the study had a median (range) of 6.2 (0.0 – 20.0) years' experience officiating at national level. Ethical approval was obtained from Dublin City University Research Ethics Committee (Appendix [1](#)) in accordance with the Declaration of Helsinki.

5.2.3 Anthropometry

As described in Chapter 3, Section [3.2.3](#).

5.2.4 Data collection

A total of 132 full game data files were collected between 2018 and 2019. Data files were collected as described in Chapter 3, Section [3.2.4](#).

5.2.5 Data processing

Data files were processed as described in Chapter 3, Section [3.2.5](#). This resulted in the exclusion of four data files. Three data files were also identified as outliers based on duration and were excluded from further analysis. This resulted in a final dataset of 125 full game data files, with a median of 3 full game data files per referee (mean = 3.2 games; range: 1 – 6 games). A breakdown of the data files collected during each division of the NFL is presented in Figure [5.1](#).

5.2.6 Movement variables

As described in Chapter 4, Section [4.2.6](#).

5.2.7 Statistical analysis

Statistical analysis was completed using SPSS (v.25) (IBM, Chicago, IL, USA). Data are presented as mean \pm SD, unless otherwise stated. Differences in activity profile between the match halves and quarters and between the four divisions were examined using the series of LMM described in Chapter 4, Section [4.2.7](#). Estimates of ES were also determined as outlined in Chapter 4, Section [4.2.7](#).

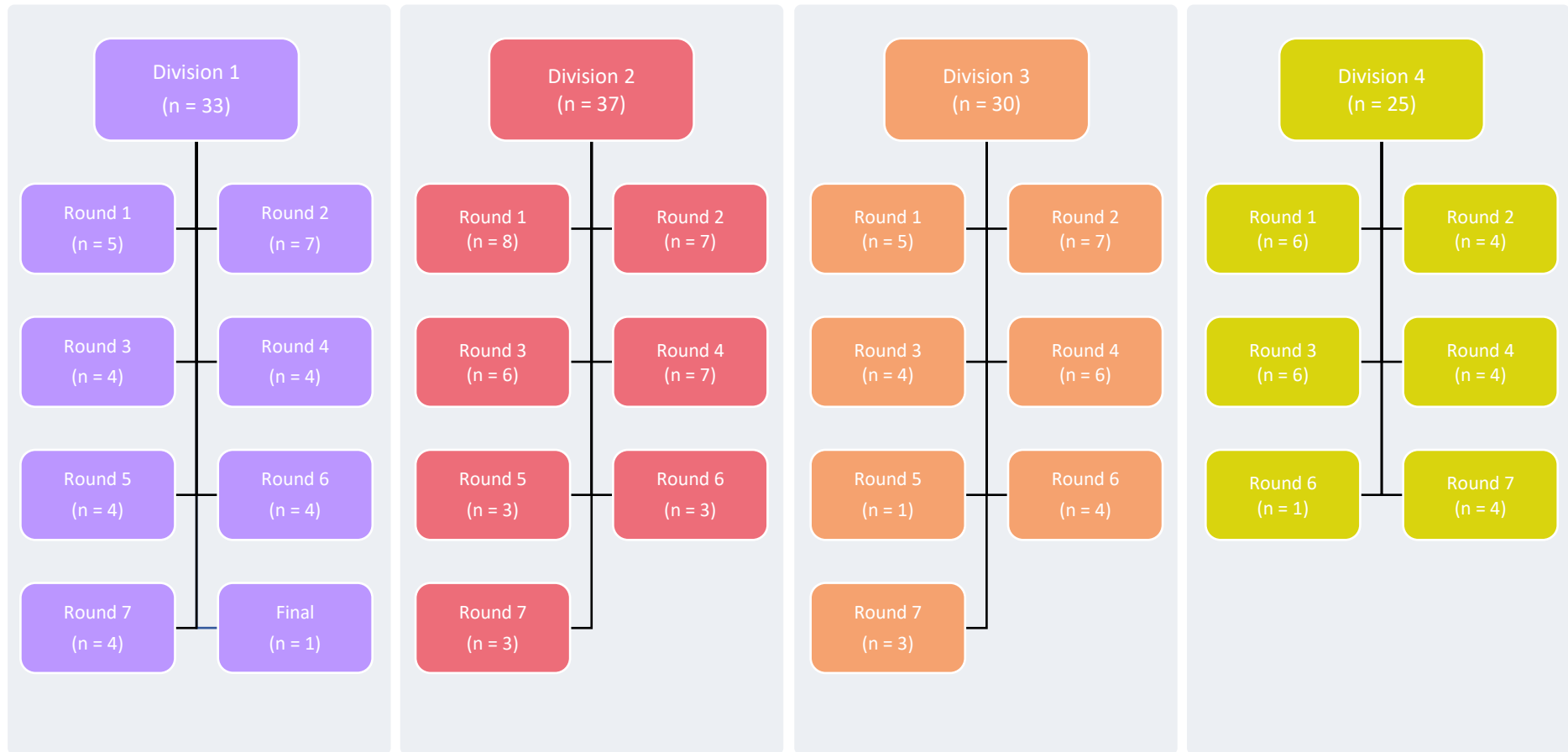


Figure 5.1. Breakdown of games in each round and division of the NFL.

5.3 Results

5.3.1 Activity profile during the NFL

5.3.1.1 Full game

The mean game duration during the NFL was 77.3 ± 1.9 min. On average, referees covered a relative distance of 119.6 ± 9.5 m·min⁻¹ and completed 2.2 ± 0.4 m·min⁻¹ of VLSM, 25.7 ± 3.5 m·min⁻¹ of walking, 36.8 ± 5.5 m·min⁻¹ of LSR, 43.2 ± 7.1 m·min⁻¹ of MSR, 11.5 ± 4.8 m·min⁻¹ of HSR and 0.4 ± 0.7 m·min⁻¹ of VHSR. The peak running speed was 6.74 ± 0.51 m·s⁻¹.

5.3.1.2 Comparisons between the first and second half

The duration of the first and second half was 37.5 ± 1.2 min and 39.9 ± 1.4 min ($P < 0.001$, ES = 1.63), respectively. The relative distance during the first and second half was 124.5 ± 10.4 m·min⁻¹ and 115.1 ± 10.4 m·min⁻¹ ($P < 0.001$, ES = -0.71), respectively. The relative distance in each movement category during the first and second half is presented in Table [5.1](#). The relative distance involving VLSM and walking was lower ($P < 0.001$) in the first half than the second half, while the relative distance in the LSR, MSR and HSR categories was higher ($P < 0.01$) in the first half than the second half. The peak running speed did not differ ($P = 0.872$, ES = -0.02) between the first (6.57 ± 0.53 m·s⁻¹) and second half (6.57 ± 0.53 m·s⁻¹).

5.3.1.3 Comparisons across the four match quarters

The relative distance was significantly different across the quarters of match play. A greater relative distance was covered during the first quarter (131.0 ± 11.3 m·min⁻¹) than

the second ($119.1 \pm 11.6 \text{ m}\cdot\text{min}^{-1}$, $P < 0.001$, $ES = -0.91$), third ($118.0 \pm 12.1 \text{ m}\cdot\text{min}^{-1}$, $P < 0.001$, $ES = -0.98$) and fourth quarters ($113.1 \pm 13.0 \text{ m}\cdot\text{min}^{-1}$, $P < 0.001$, $ES = -1.37$), respectively. The relative distance was also higher in the second ($P < 0.001$, $ES = -0.46$) and third quarter ($P < 0.001$, $ES = -0.38$) than the fourth quarter. The relative distance in each movement category during each quarter and between the quarters is presented in Table [5.2](#). The relative distance involving VLMSM and walking was lower ($P < 0.01$) in the first quarter than any other match period, while the relative distance in the LSR and MSR categories was higher ($P < 0.001$) in the first quarter than any other match period. The relative distance in the LSR and MSR categories was lower ($P < 0.001$) in the fourth quarter than any other match period. The relative distance in the HSR category during the first quarter was higher ($P < 0.001$) than the third and fourth quarters of match play. The ES for the relative distance in each movement category between the four quarters is presented in Figure [5.2](#). No significant differences in the peak running speed were observed between the quarters of match play ($ES = -0.04$ to 0.02).

Table 5.1. Relative distance in each movement category during the first and second half of match play during the NFL

	Match Period		P value	ES (95% CI)
	First Half	Second Half		
VLSM (m·min ⁻¹)	2.0 ± 0.4	2.3 ± 0.5	<0.001	0.07 (-0.18 to 0.32)
Walking (m·min ⁻¹)	25.2 ± 3.8	26.1 ± 3.8	<0.001	0.19 (-0.06 to 0.44)
LSR (m·min ⁻¹)	38.9 ± 5.5	34.9 ± 6.2	<0.001	-0.59 (-0.84 to -0.33)
MSR (m·min ⁻¹)	45.9 ± 8.2	40.6 ± 7.5	<0.001	-0.54 (-0.80 to -0.29)
HSR (m·min ⁻¹)	12.2 ± 5.3	10.8 ± 5.2	0.008	-0.16 (-0.40 to 0.09)
VHSR (m·min ⁻¹)	0.4 ± 0.8	0.3 ± 0.7	0.884	-0.01 (-0.26 to 0.24)
HSR+VHSR (m·min ⁻¹)	12.5 ± 5.6	11.2 ± 5.6	0.008	-0.15 (-0.40 to 0.09)

Data are presented as mean ± SD. ES, effect size; VLSM, very low-speed movement; LSR, low-speed running; MSR, moderate-speed running; HSR, high-speed running; VHSR, very-high speed running.

Table 5.2. Relative distance in each movement category across the four quarters of match play during the NFL

	Match Period			
	First Quarter	Second Quarter	Third Quarter	Fourth Quarter
VLSM (m·min ⁻¹)	1.9 ± 0.5	2.1 ± 0.6 ^a	2.2 ± 0.6 ^a	2.3 ± 0.6 ^{a,b}
Walking (m·min ⁻¹)	24.0 ± 4.2	26.2 ± 4.4 ^a	25.2 ± 3.9 ^{c,d}	27.0 ± 4.4 ^{a,e}
LSR (m·min ⁻¹)	41.4 ± 6.5	36.8 ± 6.0 ^a	36.9 ± 7.1 ^a	33.6 ± 7.2 ^{a,b,e}
MSR (m·min ⁻¹)	50.0 ± 9.5	42.5 ± 9.6 ^a	42.7 ± 8.7 ^a	39.1 ± 9.4 ^{a,b,e}
HSR (m·min ⁻¹)	13.3 ± 7.1	11.2 ± 5.2	10.7 ± 6.1 ^a	10.7 ± 6.5 ^a
VHSR (m·min ⁻¹)	0.4 ± 1.0	0.3 ± 1.0	0.3 ± 0.9	0.4 ± 1.2
HSR+VHSR (m·min ⁻¹)	13.7 ± 7.4	11.5 ± 5.6	11.0 ± 6.6 ^a	11.1 ± 7.0 ^a

Data are presented as mean ± SD. ^a P <0.001 vs. First Quarter; ^b P <0.001 vs. Second Quarter; ^c P <0.01 vs. First Quarter; ^d P <0.01 vs. Second Quarter; ^e P <0.001 vs. Third Quarter. VLSM, very low-speed movement; LSR, low-speed running; MSR, moderate-speed running; HSR, high-speed running; VHSR, very high-speed running.

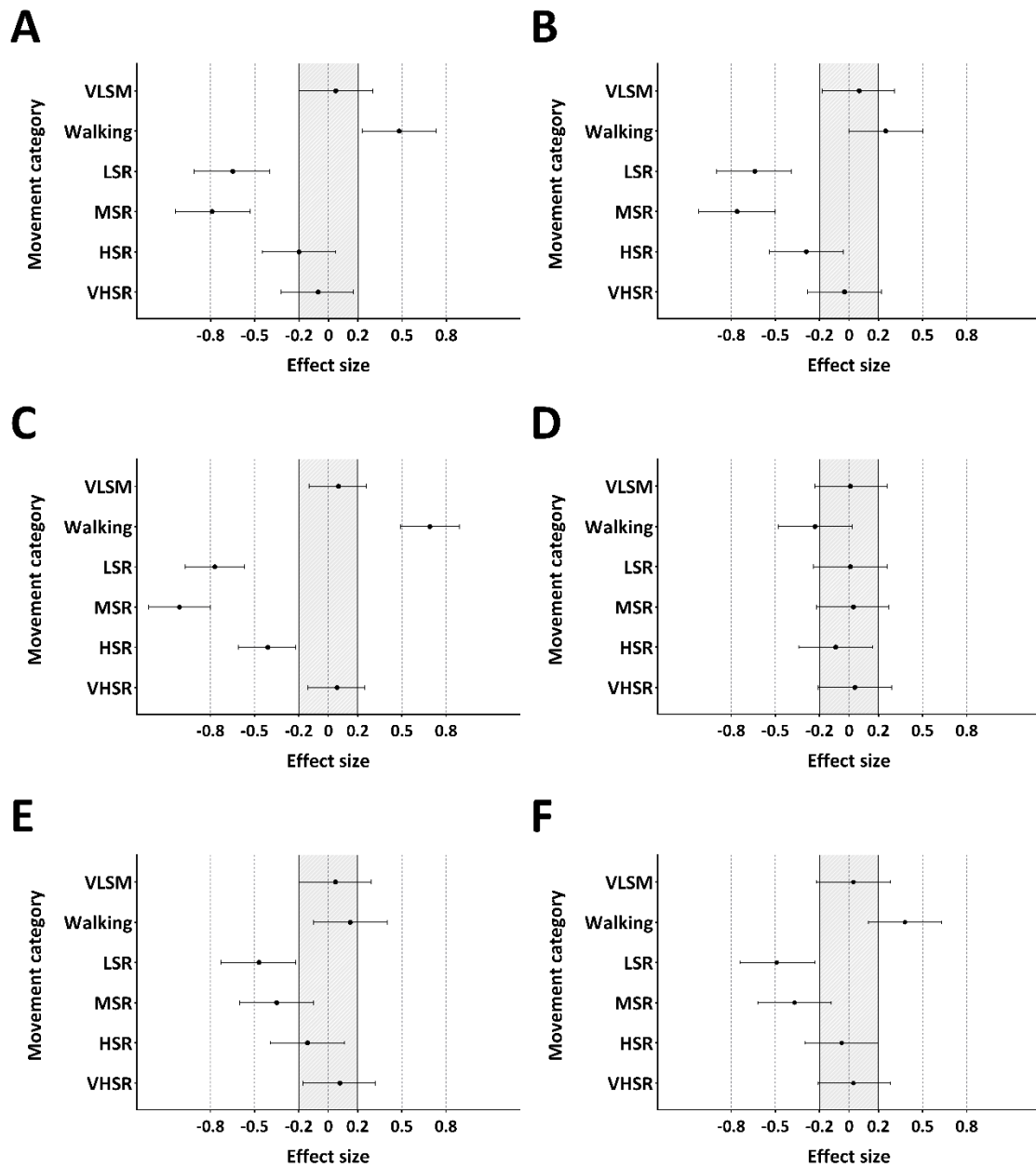


Figure 5.2. Effect size plots of the change in relative distance in each movement category from the first to second (A), first to third (B), first to fourth (C), second to third (D), second to fourth (E), and third to fourth (F) quarter of the NFL. Circles represent the ES and the horizontal lines represent the 95% confidence interval. VLSM, very low-speed movement; LSR, low-speed running; MSR, moderate-speed running; HSR, high-speed running; VHSR, very high-speed running.

5.3.2 NFL division comparisons

5.3.2.1 Full game

The mean game duration during Division 1, Division 2, Division 3, and Division 4 games was 77.6 ± 2.1 min, 77.4 ± 1.8 min, 77.4 ± 2.6 min, and 76.6 ± 2.0 min, during which referees covered a relative distance of 119.3 ± 9.5 m·min⁻¹, 120.6 ± 10.5 m·min⁻¹, 118.2 ± 8.8 m·min⁻¹ and 120.2 ± 8.9 m·min⁻¹, respectively. There were no significant differences in mean game duration (ES = 0.02 to 0.34) or relative distance (ES = -0.23 to 0.07) between the four divisions.

The relative distance in each movement category across the full game for each of the four divisions of the NFL is presented in Table 5.3. There were no significant differences in relative distance in the VLSM (ES = -0.02 to 0.01), walking (ES = -0.18 to 0.16), LSR (ES = -0.20 to 0.18), MSR (ES = -0.23 to 0.11), HSR (ES = -0.08 to 0.11) or VHSR (ES = -0.03 to 0.12) categories between the four divisions of the NFL. There were no significant differences in peak running speed between Division 1 (6.62 ± 0.45 m·s⁻¹), Division 2 (6.80 ± 0.50 m·s⁻¹), Division 3 (6.68 ± 0.48 m·s⁻¹) and Division 4 (6.89 ± 0.62 m·s⁻¹) (ES = -0.13 to 0.40).

5.3.2.2 Comparisons between the first and second half

The relative distance in the first half was 124.4 ± 10.2 m·min⁻¹, 124.3 ± 12.1 m·min⁻¹, 124.5 ± 9.5 m·min⁻¹ and 125.2 ± 9.4 m·min⁻¹ in Division 1, Division 2, Division 3, and Division 4, respectively. The relative distance in the second half was 114.8 ± 10.7 m·min⁻¹, 117.2 ± 10.5 m·min⁻¹, 112.5 ± 9.5 m·min⁻¹, and 115.6 ± 10.6 m·min⁻¹ in Division 1, Division 2, Division 3, and Division 4, respectively. The relative distance in the first half was higher

than the second half in Division 1 ($P < 0.001$, $ES = -0.68$), Division 2 ($P < 0.001$, $ES = -0.56$), Division 3 ($P < 0.001$, $ES = -0.85$) and Division 4 ($P < 0.001$, $ES = -0.79$). There was no significant difference in relative distance for the first half ($ES = -0.29$ to 0.21) or second half ($ES = -0.25$ to 0.21) between the four divisions of the NFL.

The relative distance in each movement category during the first and second half in the four divisions of the NFL is presented in Table [5.4](#). The relative distance in the VLSM category was lower ($P < 0.01$) in the first half than the second half for all four divisions of the NFL, while the relative distance in the walking category was lower ($P < 0.01$) in the first half than the second half in Division 1 only. The relative distance in the LSR and MSR categories was higher ($P < 0.001$) in the first half than the second half for all four divisions of the NFL. There was no significant difference in the relative distance in the HSR or VHSR categories or in peak running speed between halves in any of the four divisions of the NFL. There were no significant between group differences in the relative distance in any movement category during the first or second half.

5.3.2.3 Comparisons across the four match quarters

The differences in relative distance across the four quarters of match play for each of the four divisions of the NFL are presented in Figure [5.3](#). For all four divisions, the relative distance in the first quarter was higher ($P < 0.001$) than any other match period. The relative distance in the second quarter was also higher than the fourth quarter in Division 1 ($P = 0.005$) and Division 3 ($P < 0.001$).

The relative distance in each movement category during each quarter and between the quarters for each of the four divisions of the NFL is presented in Table [5.5](#). The relative

distance involving VLSM was lower ($P < 0.01$) in the first and second quarter than the fourth quarter in Division 1 and lower ($P < 0.01$) in the first quarter than the third and fourth quarters of Division 3. The relative distance in the VLSM category was also lower ($P < 0.001$) in the second quarter than the fourth quarter in Division 3. The relative distance involving walking was lower ($P < 0.01$) in the first quarter than the second and fourth quarters in Division 1, Division 2, and Division 4, and lower ($P < 0.01$) in the third quarter than the fourth quarter in Division 1 and Division 2. In Division 3, relative distance involving walking was lower ($P < 0.001$) in the first quarter than the fourth quarter only. The relative distance involving LSR and MSR was higher ($P < 0.01$) in the first quarter than any other match period in all four divisions of the NFL. The relative distance in the LSR category was lower ($P < 0.01$) in the fourth quarter than any other match period in Division 1, Division 3, and Division 4, while relative distance in the MSR category was lower ($P < 0.01$) in the fourth quarter than any other match period in Division 1. The relative distance involving HSR was higher ($P < 0.01$) in the first quarter than the third and fourth quarters in Division 3. There were no differences in HSR across quarters in any other division. There was also no difference in the relative distance in the VHSR category or peak running speed across the four quarters of match play during any of the four divisions. There were no differences in the relative distance in any movement category during the four quarters between the four divisions of the NFL.

Table 5.3. Relative distance in each movement category during the full game in the four divisions of the NFL

	Division 1	Division 2	Division 3	Division 4
VLSM (m·min ⁻¹)	2.2 ± 0.4	2.1 ± 0.5	2.2 ± 0.4	2.1 ± 0.3
Walking (m·min ⁻¹)	26.2 ± 3.2	25.4 ± 3.4	25.3 ± 3.7	25.7 ± 4.0
LSR (m·min ⁻¹)	37.1 ± 4.3	37.7 ± 5.7	37.4 ± 5.5	34.5 ± 6.2
MSR (m·min ⁻¹)	43.4 ± 7.5	43.6 ± 7.6	42.2 ± 6.5	43.3 ± 6.9
HSR (m·min ⁻¹)	10.2 ± 4.1	11.4 ± 5.0	10.8 ± 4.4	13.9 ± 5.2
VHSR (m·min ⁻¹)	0.2 ± 0.3	0.3 ± 0.5	0.3 ± 0.8	0.6 ± 1.0
HSR+VHSR (m·min ⁻¹)	10.4 ± 4.3	11.8 ± 5.2	11.1 ± 4.9	14.6 ± 5.8

Data are presented as mean ± SD. VLSM, very low-speed movement; LSR, low-speed running; MSR, moderate-speed running; HSR, high-speed running; VHSR, very high-speed running.

Table 5.4. Relative distance in each movement category during the first and second half and between the four divisions of the NFL

	League Division	Match Period	
		First Half	Second Half
VLSM (m·min ⁻¹)	Division 1	2.0 ± 0.5	2.4 ± 0.5 ^a
	Division 2	2.0 ± 0.5	2.2 ± 0.5 ^a
	Division 3	2.0 ± 0.4	2.4 ± 0.5 ^a
	Division 4	1.9 ± 0.3	2.2 ± 0.5 ^b
Walking (m·min ⁻¹)	Division 1	25.6 ± 3.3	26.8 ± 3.7 ^b
	Division 2	25.1 ± 3.6	25.8 ± 3.7
	Division 3	24.7 ± 4.0	25.8 ± 3.8
	Division 4	25.4 ± 4.5	26.0 ± 3.9
LSR (m·min ⁻¹)	Division 1	39.1 ± 4.5	35.3 ± 5.0 ^a
	Division 2	38.9 ± 5.5	36.5 ± 6.7 ^a
	Division 3	40.0 ± 5.3	35.0 ± 6.2 ^a
	Division 4	37.4 ± 6.9	31.8 ± 6.2 ^a
MSR (m·min ⁻¹)	Division 1	46.8 ± 8.2	40.2 ± 8.1 ^a
	Division 2	45.6 ± 9.6	41.8 ± 7.3 ^a
	Division 3	45.4 ± 7.5	39.3 ± 6.4 ^a
	Division 4	45.9 ± 7.1	41.0 ± 8.3 ^a
HSR (m·min ⁻¹)	Division 1	10.7 ± 4.6	9.8 ± 4.2
	Division 2	12.3 ± 5.3	10.6 ± 5.3
	Division 3	12.0 ± 5.8	9.6 ± 4.0
	Division 4	14.0 ± 5.2	13.9 ± 6.6
VHSR (m·min ⁻¹)	Division 1	0.2 ± 0.4	0.2 ± 0.4
	Division 2	0.4 ± 0.7	0.3 ± 0.6
	Division 3	0.3 ± 0.9	0.3 ± 0.8
	Division 4	0.6 ± 0.9	0.7 ± 1.1
HSR+VHSR (m·min ⁻¹)	Division 1	10.9 ± 4.8	10.0 ± 4.4
	Division 2	12.7 ± 5.5	10.9 ± 5.5
	Division 3	12.4 ± 6.3	10.0 ± 4.5
	Division 4	14.6 ± 5.5	14.5 ± 7.3

Data are presented as mean ± SD. ^a P <0.001 vs. First Half; ^b P <0.01 vs. First Half. VLSM, very low-speed movement; LSR, low-speed running; MSR, moderate-speed running; HSR, high-speed running; VHSR, very high-speed running.

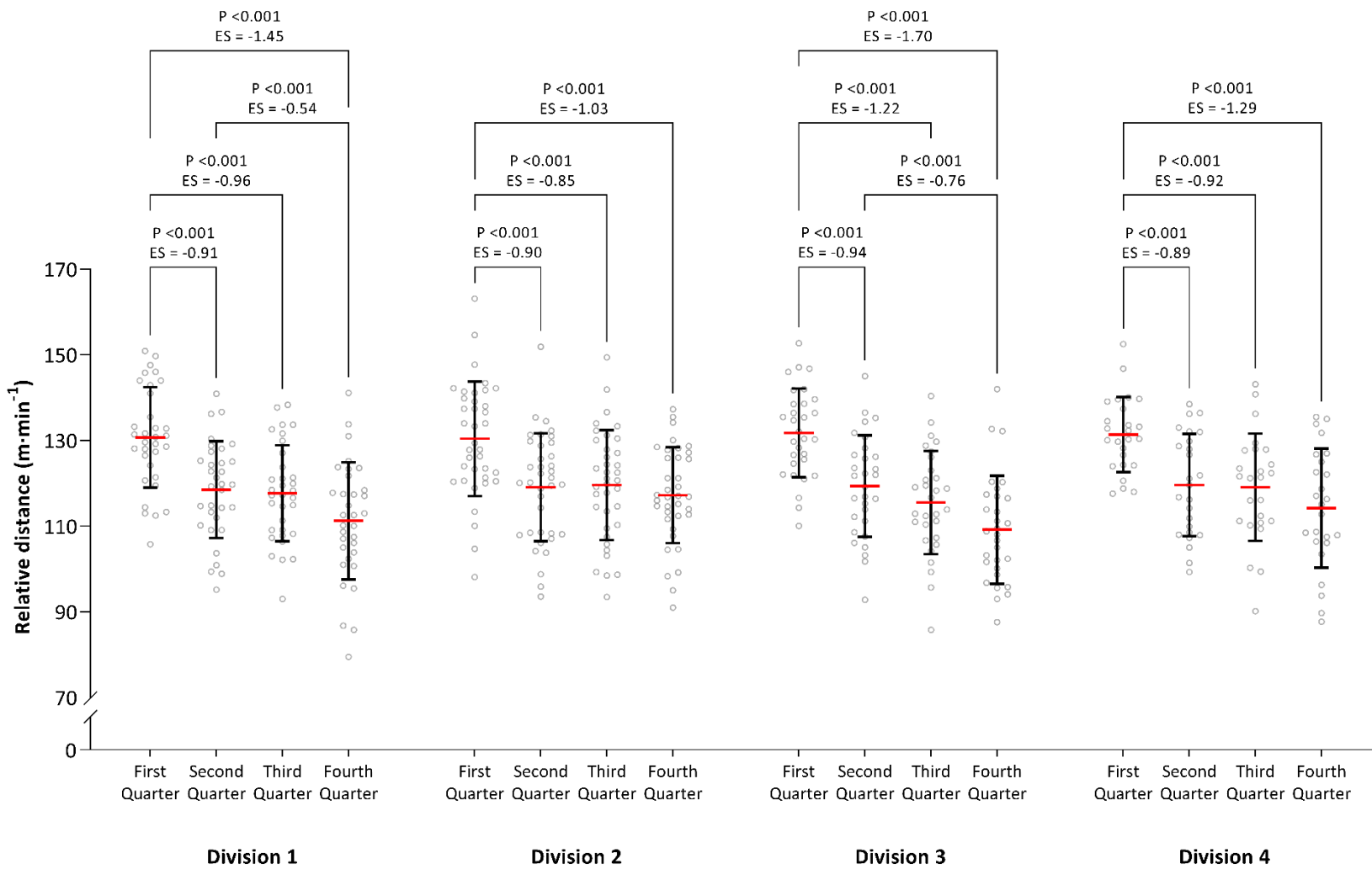


Figure 5.3. Relative distance across each quarter of match play for the four divisions of the NFL. Data are presented as mean with error bars representing SD and circles representing individual data points.

Table 5.5. Relative distance in each movement category across the four quarters of match play between the four divisions of the NFL

	League Division	Match Period			
		First Quarter	Second Quarter	Third Quarter	Fourth Quarter
VLSM (m·min ⁻¹)	Division 1	1.9 ± 0.5	2.2 ± 0.7	2.2 ± 0.7	2.5 ± 0.6 ^{a,d}
	Division 2	2.0 ± 0.5	2.2 ± 0.6	2.2 ± 0.6	2.2 ± 0.6
	Division 3	1.9 ± 0.4	2.1 ± 0.5	2.3 ± 0.6 ^c	2.5 ± 0.6 ^{a,b}
	Division 4	1.9 ± 0.4	2.0 ± 0.5	2.1 ± 0.7	2.2 ± 0.6
Walking (m·min ⁻¹)	Division 1	24.0 ± 3.9	27.1 ± 3.9 ^a	25.7 ± 3.4	28.0 ± 4.8 ^{a,f}
	Division 2	24.0 ± 3.8	25.6 ± 4.3 ^c	24.7 ± 3.7	26.8 ± 4.5 ^{a,f}
	Division 3	23.8 ± 4.2	25.5 ± 4.6	25.2 ± 4.4	26.6 ± 4.1 ^a
	Division 4	24.2 ± 5.1	26.7 ± 4.6 ^a	25.2 ± 4.2	26.6 ± 4.1 ^c
LSR (m·min ⁻¹)	Division 1	41.6 ± 6.0	36.9 ± 4.8 ^a	37.3 ± 5.0 ^a	33.5 ± 6.4 ^{a,d,e}
	Division 2	41.3 ± 6.0	36.8 ± 5.7 ^a	38.4 ± 7.2 ^c	36.4 ± 8.1 ^a
	Division 3	42.8 ± 6.2	37.6 ± 6.0 ^a	37.0 ± 8.3 ^a	33.3 ± 6.6 ^{a,b,f}
	Division 4	39.7 ± 8.2	35.6 ± 7.7 ^a	34.3 ± 7.3 ^a	30.2 ± 6.3 ^{a,b,f}
MSR (m·min ⁻¹)	Division 1	52.1 ± 10.4	42.1 ± 9.2 ^a	43.0 ± 10.0 ^a	37.1 ± 9.4 ^{a,d,e}
	Division 2	49.3 ± 10.3	42.9 ± 11.0 ^a	43.2 ± 8.7 ^a	41.1 ± 8.5 ^a
	Division 3	49.1 ± 9.1	43.4 ± 9.2 ^c	41.1 ± 7.9 ^a	38.0 ± 8.6 ^{a,d}
	Division 4	49.5 ± 7.6	41.6 ± 8.8 ^a	43.5 ± 8.1 ^c	40.0 ± 11.4 ^a
HSR (m·min ⁻¹)	Division 1	10.9 ± 5.9	10.1 ± 5.5	9.4 ± 4.6	10.0 ± 5.8
	Division 2	13.6 ± 6.8	11.2 ± 5.2	10.7 ± 6.9	10.4 ± 6.0
	Division 3	13.9 ± 8.0	10.5 ± 4.9	9.7 ± 4.9 ^c	8.4 ± 5.4 ^a
	Division 4	15.3 ± 7.3	13.3 ± 4.8	13.4 ± 7.2	14.7 ± 7.9

Table 5.5 (cont.). Relative distance in each movement category across the four quarters of match play between the four divisions of the NFL

	League Division	Match Period			
		First Quarter	Second Quarter	Third Quarter	Fourth Quarter
VHSR (m·min ⁻¹)	Division 1	0.2 ± 0.6	0.2 ± 0.4	0.2 ± 0.5	0.2 ± 0.7
	Division 2	0.4 ± 1.0	0.4 ± 1.1	0.2 ± 0.7	0.4 ± 1.2
	Division 3	0.3 ± 0.6	0.3 ± 1.2	0.3 ± 1.0	0.4 ± 1.2
	Division 4	0.7 ± 1.5	0.4 ± 0.9	0.7 ± 1.5	0.7 ± 1.5
HSR+VHSR (m·min ⁻¹)	Division 1	11.1 ± 6.1	10.2 ± 5.7	9.6 ± 4.8	10.2 ± 6.0
	Division 2	14.0 ± 7.1	11.7 ± 5.6	11.0 ± 7.2	10.8 ± 6.3
	Division 3	14.2 ± 8.4	10.8 ± 5.2	10.0 ± 5.4 ^c	8.8 ± 6.2 ^a
	Division 4	16.0 ± 7.5	13.7 ± 5.2	14.1 ± 8.2	15.3 ± 8.5

Data are presented as mean ± SD. ^a P <0.001 vs. First Quarter; ^b P <0.001 vs. Second Quarter; ^c P <0.01 vs. First Quarter; ^d P <0.01 vs. Second Quarter; ^e P <0.001 vs. Third Quarter; ^f P <0.01 vs. Third Quarter. VLSM, very low-speed movement; LSR, low-speed running; MSR, moderate-speed running; HSR, high-speed running; VHSR, very high-speed running.

5.4 Summary

The relative distance covered by the referee during NFL games was 119.6 m·min⁻¹. The majority of this distance was covered at low and moderate speeds with only 10% covered at high and very high-speed. The relative distance and distance covered within each movement category except VH SR was different between the first and second half of NFL games. There was a higher relative, LSR, and MSR distance and a lower VLSM and walking distance in the first quarter than any other match period. In addition, the HSR distance in the third and fourth quarter was lower than the first quarter. No differences in VH SR or peak running speed were found between the four quarters of match play during NFL games.

There was no difference in the relative distance, distance covered in any movement category or peak running speed between the four divisions of the NFL. For all four divisions, the relative distance was higher during the first half than the second half and during the first quarter than any other quarter. The distance covered in the LSR and MSR categories was higher in the first half than the second half and during the first quarter than any other match quarter. There was no difference in HSR, VH SR or peak running speed between the first and second half and no difference in HSR across the four quarters in Division 1, Division 2, or Division 4. No differences were found in VH SR distance or peak running speed between quarters in all four divisions. The relative distance and distance covered within each movement category across the four quarters of match play was similar between all four divisions of the NFL.

CHAPTER VI

STUDY 4

COMPARISON OF THE ACTIVITY PROFILE OF ELITE GAELIC FOOTBALL REFEREES BETWEEN THE ALL-IRELAND CHAMPIONSHIP AND THE NATIONAL FOOTBALL LEAGUE AND THE INFLUENCE OF AGE, EXPERIENCE, AND AEROBIC FITNESS

6.1 Introduction

6.1.1 Rationale

Elite GFR are required to achieve a minimum score on a field-based fitness test prior to the NFL and AIC. Failure to meet the minimum fitness threshold results in elimination from the panel for the respective competition. At present, the minimum fitness level is lower for the NFL than the AIC, primarily due to the fact that the intensity of games in the NFL is thought to be lower than the AIC (11, 160). To date, no studies have compared the activity profile of elite Gaelic football players or referees between the NFL and AIC.

Several factors are thought to contribute to differences in intensity between the NFL and AIC. Firstly, the competition structure in the NFL involves a round robin format whereas the AIC is predominantly knockout. As a result, teams will often use the NFL as an opportunity to incorporate new players into their team and experiment with different tactical approaches. Secondly, the AIC, in particular the AIS, draws larger attendances, television audiences and press coverage. Finally, the AIC is regarded as the premier annual competition in Gaelic football with the highest ranked teams typically contesting the latter stages of the competition.

Previous studies examining soccer referees during match play have identified a number of contextual factors that influence their activity profile (13). Soccer referees classified as 'older' (43 – 48 years) were found to cover 6 – 8% less total and 15 – 40% less HIR distance ($>5.5 \text{ m}\cdot\text{s}^{-1}$) and to complete 17 – 54% fewer sprints than referees categorised as 'intermediate' (37 – 42 years) and 'young' (31 – 36 years) (142). The reduced HIR and sprint distance of 'older' referees did not however increase their distance from fouls compared to 'intermediate' and 'young' referees. It may be that 'older' referees have more experience and 'read the game' better, resulting in a reduced total, HSR and sprinting distance (142). Despite no published research examining the effect of age on the activity profile of elite GFR, the mandatory retirement age at national level is currently 50 years.

Field-based fitness tests are frequently used as part of the referee selection process by governing bodies of IFTS (13, 54). The YIRT1 is the most extensively researched and one of the most commonly used tests to estimate aerobic fitness in soccer referees (13, 149). The YIRT1 has been criticised for lacking content validity in the examination of elite IFTS (13), however performance in the YIRT1 was found to be positively associated with both the HIR distance ($>3.6 \text{ m}\cdot\text{s}^{-1}$) ($r = 0.59$) and HSR distance ($>5.0 \text{ m}\cdot\text{s}^{-1}$) ($r = 0.42$) completed by elite soccer referees during match play (119). Despite the use of the YIRT1 as part of the GAA selection criteria prior to the NFL and AIC, no studies have evaluated the relation between performance in the YIRT1 and the activity profile of elite GFR during competitive match play. The purpose of this study was therefore to compare the activity profile of elite GFR between the NFL and AIC and to examine the influence of age, experience level, and aerobic fitness on their activity profile during both competitions.

6.1.2 Study aims

1. To compare the activity profile of elite GFR between the NFL and the AIC
2. To compare the activity profile of elite GFR during the first and second half and the four match quarters between the NFL and the AIC
3. To examine the influence of age on the activity profile of elite GFR during the NFL and the AIC
4. To examine the influence of experience level on the activity profile of elite GFR during the NFL and the AIC
5. To examine the influence of aerobic fitness on the activity profile of elite GFR during the NFL and the AIC

6.1.3 Study hypothesis

1. There will be significantly more total and HSR distance covered and a higher peak running speed during the AIC than the NFL
2. The total and HSR distance and peak running speed will be significantly higher in the second half and fourth quarter of the AIC than the NFL
3. Age will be inversely related to total, HSR and VHSR distance and peak running speed during games in both the NFL and the AIC
4. Experience level will be inversely related to total distance but not HSR distance, VHSR distance or peak running speed during games in both the NFL and the AIC
5. Aerobic fitness will be directly related to total, HSR and VHSR distance and peak running speed during games in both the NFL and the AIC

6.2 Methodology

6.2.1 Overview of study design

A longitudinal observational study design was used to compare the differences in activity profile of elite GFR between the NFL and AIC during games played between 2016 and 2019. Match activity data were collected using GPS and GNSS technology to quantify the distances and running speeds achieved during each competition. Data files were also partitioned into three groups to examine the influence of age, experience level, and aerobic fitness on the activity profile of elite GFR during both the NFL and AIC.

6.2.2 Participants

As described in Chapter 4, Section [4.2.2](#) and Chapter 5, Section [5.2.2](#) for the AIC and NFL, respectively. Ethical approval was obtained from Dublin City University Research Ethics Committee (Appendix [1](#) and Appendix [2](#)) in accordance with the Declaration of Helsinki.

6.2.3 Anthropometry

As described in Chapter 3, Section [3.2.3](#).

6.2.4 Data collection

Data files were collected as described in Chapter 3, Section [3.2.4](#) and include those outlined in Chapter 4, Section [4.2.4](#) and Chapter 5, Section [5.2.4](#) for the AIC and NFL, respectively.

6.2.5 Data processing

Data files were processed as described in Chapter 3, Section [3.2.5](#). Data files outlined in Chapter 4, Section [4.2.5](#) and Chapter 5, Section [5.2.5](#) for the AIC and NFL, respectively, were included in the analysis.

6.2.6 Movement variables

As described in Chapter 4, Section [4.2.6](#).

6.2.7 Age and experience level

The age of the referee was recorded as their age on the date of each game that they officiated. Experience level was recorded as the number of years officiating in the NFL and the number of years officiating in the AIC. The data files were subsequently divided into three age groups (low, moderate, high) and three experience groups (low, moderate, high NFL experience; low, moderate, high AIC experience) based on the rank order of each. The analysis was completed separately for data files collected in the NFL and AIC. A breakdown of each group is presented in [Table 6.1](#).

6.2.8 Aerobic fitness

The YIRT1 is a 2 x 20 m shuttle run test undertaken at progressively increasing velocities and controlled by audio signals. Each 40 m run is interspersed with a 10 s period of active recovery consisting of jogging or walking 10 m. The test begins at 10 km·h⁻¹ and increases to 13 km·h⁻¹ for the third and fourth shuttle runs. The speed increases to 13.5 – 14 km·h⁻¹ for the next seven runs after which it increases by 0.5 km·h⁻¹ following every eight runs (320 m). Participants receive a warning the first time that they fail to complete

a run within the allotted time. A second failure results in their removal from the test. The final speed level and distance covered by each participant is recorded.

All tests during the present study were performed on a 4G playing surface with lines marked at the start point and 20 m. Participants were familiar with the testing procedures. Based on the distance covered during the YIRT1 prior to the start of the NFL and AIC each year, data files were subsequently divided into three groups (low, moderate, high) according to the rank order. The analysis was completed separately for data files collected during the NFL and AIC. A breakdown of each group is presented in Table [6.1](#).

6.2.9 Statistical analysis

Statistical analysis was completed using SPSS (v.25) (IBM, Chicago, IL, USA). Differences in activity profile between the full game, halves and quarters of the NFL and AIC were compared using the series of LMM described in Chapter 4, Section [4.2.7](#). Data are presented as mean \pm SD, unless otherwise stated. Estimates of ES were determined as outlined in Chapter 4, Section [4.2.7](#).

The influence of age, experience, and aerobic fitness on the activity profile were also examined using a series of LMM. Data are presented as estimated marginal mean (EMM) with standard error (SE). Age, experience, aerobic fitness, and playing season were fitted as fixed effects with referee treated as a random effect. Prior to the analysis, multicollinearity tests were performed for all variables using the variance inflation factor (VIF). In all cases the VIF was <5 and were therefore treated independently. The LMM were conducted separately for the NFL and the AIC. Normality assumptions of the residuals were examined using plots of the model residuals and the predicted values.

Where the assumptions were violated, the dependant variable was log transformed. Significant main effects and interactions were probed using Bonferroni adjusted contrasts. Estimates of ES were determined as outlined in Chapter 4, Section 4.2.7. The significance level was set at $\alpha \leq 0.05$ for all tests.

Table 6.1. Age, experience level, and aerobic fitness of referees in each group for games in the NFL and AIC

		Group 1 (<i>Low</i>)			Group 2 (<i>Moderate</i>)			Group 3 (<i>High</i>)		
		<i>n</i>	Mean	Range	<i>n</i>	Mean	Range	<i>n</i>	Mean	Range
Age (years)	NFL	43	32.3 ± 3.0 ^{a,b}	25 – 36	43	38.4 ± 0.9 ^b	37 – 40	39	44.2 ± 2.6	41 – 50
	AIC	75	35.2 ± 2.4 ^{a,b}	30 – 38	65	39.9 ± 0.8 ^b	39 – 41	59	44.2 ± 1.9	42 – 49
NFL Experience (years)	NFL	42	2.4 ± 1.2 ^{a,b}	0 – 4	51	6.6 ± 1.1 ^b	5 – 8	30	12.8 ± 2.8	9 – 20
	AIC	76	5.1 ± 0.9 ^{a,b}	3 – 6	69	7.8 ± 0.8 ^b	7 – 9	56	14.5 ± 2.6	10 – 20
AIC Experience (years)	NFL	62	0 ± 0 ^{a,b}	0	20	2.2 ± 0.8 ^b	1 – 3	41	7.4 ± 3.9	4 – 16
	AIC	68	1.7 ± 1.1 ^{a,b}	0 – 3	73	5.1 ± 0.8 ^b	4 – 6	60	11.7 ± 3.2	7 – 16
Aerobic Fitness (m)	NFL	52	1,439 ± 36 ^{a,b}	1,400 – 1,480	34	1,552 ± 34 ^b	1,520 – 1,600	37	1,803 ± 136	1,640 – 2,160
	AIC	86	1,591 ± 34 ^{a,b}	1,560 – 1,640	57	1,731 ± 33 ^b	1,680 – 1,760	56	1,950 ± 163	1,800 – 2,280

Data are presented as mean ± SD with sample size *n* and range. ^a P <0.001 vs. Moderate; ^b P <0.001 vs. High. NFL, National Football League; AIC, All-Ireland Championship.

6.3 Results

6.3.1 National Football League and All-Ireland Championship comparison

6.3.1.1 Full game

The mean game duration was longer ($P < 0.001$, $ES = 0.41$) during the AIC than the NFL. There was no difference in relative distance ($P = 0.382$, $ES = 0.07$) between the NFL and AIC. The relative distance in each movement category during the NFL and AIC is presented in Figure [6.1](#) and Figure [6.2](#). No differences were found for relative distance in the VLMS ($P = 0.343$, $ES = -0.01$), LSR ($P = 0.217$, $ES = 0.10$), MSR ($P = 0.579$, $ES = 0.05$), HSR ($P = 0.130$, $ES = 0.13$), and VHSR ($P = 0.736$, $ES = -0.02$) categories between the NFL and AIC. Walking distance was higher in the AIC than the NFL ($P = 0.002$, $ES = 0.24$). There was no difference in peak running speed ($P = 0.864$, $ES = 0.02$) between the NFL and AIC.

6.3.1.2 Differences between the first and second half

There was no significant difference in the mean duration of the first half ($ES = 0.26$) between the NFL and AIC, but the second half was longer ($P < 0.001$, $ES = 0.55$) during the AIC than the NFL. There was no significant difference in the relative distance in the first half ($P = 0.861$, $ES = 0.02$) or second half ($P = 0.159$, $ES = 0.13$) between the NFL and AIC. The relative distance in each movement category during the first and second half of the NFL and AIC is presented in Figure [6.3](#) and Figure [6.4](#). No differences were found in the first half for relative distance in the VLMS ($P = 0.520$, $ES = -0.01$), LSR ($P = 0.056$, $ES = 0.17$), MSR ($P = 0.457$, $ES = 0.03$), HSR ($P = 0.181$, $ES = 0.13$), and VHSR ($P = 0.769$, $ES = -0.02$) categories or in the second half for relative distance in the VLMS ($P = 0.277$, $ES = -0.01$), LSR ($P = 0.729$, $ES = 0.03$), MSR ($P = 0.800$, $ES = 0.02$), HSR ($P = 0.145$, $ES = 0.14$), or VHSR

($P = 0.364$, $ES = -0.07$) categories between the NFL and AIC. The relative distance in the walking category was higher during the first half ($P = 0.007$, $ES = 0.23$) and second half ($P = 0.002$, $ES = 0.26$) of the AIC than the NFL. There was no difference in peak running speed in the first half ($P = 0.613$, $ES = -0.06$) or second half ($P = 0.836$, $ES = 0.03$) between the NFL and AIC.

6.3.1.3 Differences across the four match quarters

The relative distance across each quarter of match play during the NFL and AIC is presented in Figure [6.5A](#). No significant difference in relative distance was found between the NFL and AIC during any quarter of match play ($ES = -0.22$ to 0.03). There was also no significant difference between the NFL and AIC for relative distance in the VLMS ($ES = -0.03$ to 0.01), MSR ($ES = -0.03$ to 0.10), HSR ($ES = 0.08$ to 0.23), or VHSR ($ES = -0.07$ to -0.02) categories during any quarter of match play. The relative distance in the walking category during the second quarter of the AIC was higher ($P = 0.001$, $ES = 0.35$) than in the NFL. The relative distance in the LSR category was higher ($P = 0.004$, $ES = -0.29$) during the first quarter of the NFL than in the AIC. No other significant differences were found during the four quarters of match play for relative distance in the walking or LSR categories between the NFL and AIC. The relative distance in the HSR and VHSR categories combined across each quarter of match play during the NFL and AIC is presented in Figure [6.5B](#). There was no significant difference between the NFL and AIC for peak running speed during any quarter of match play ($ES = 0.00$ to 0.09). The ES for the relative distance in each movement category between the NFL and AIC during the first and second half and four quarters is presented in Figure [6.6](#).

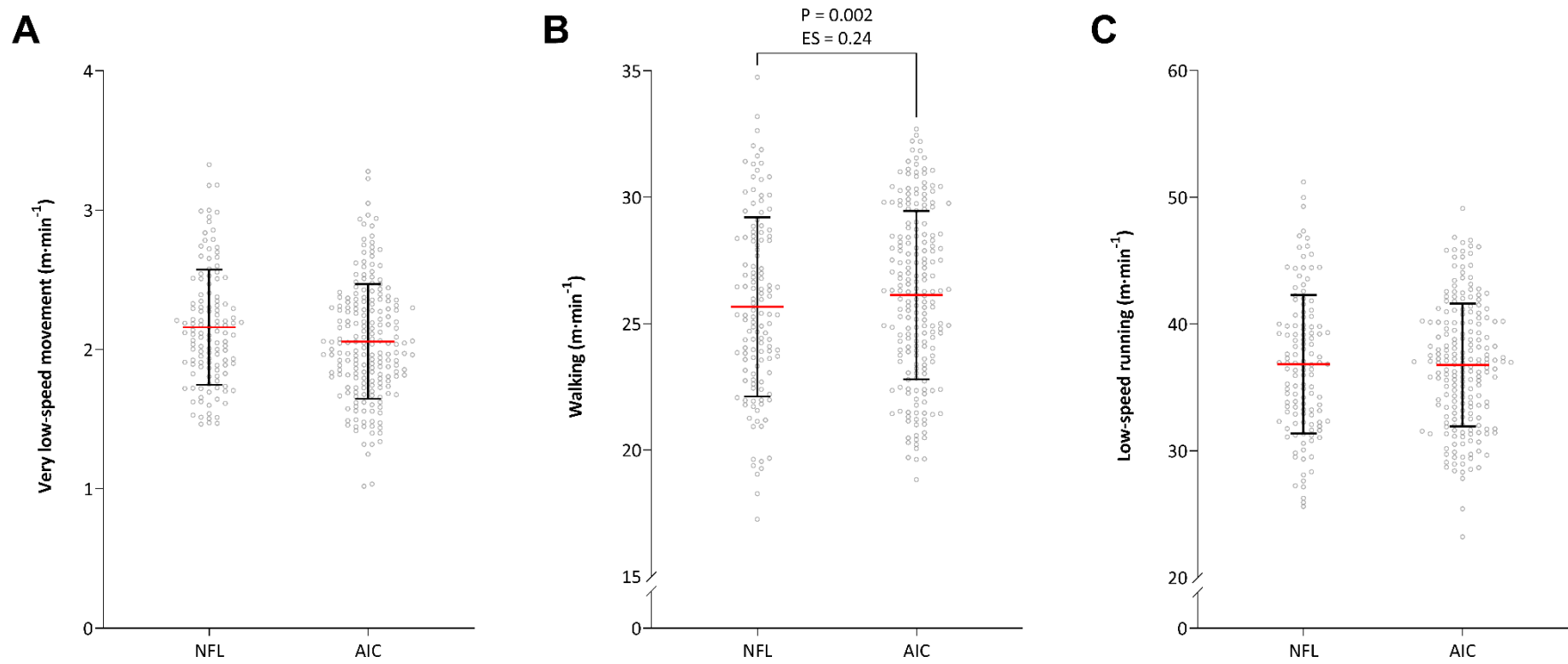


Figure 6.1. Relative distance in the VLSM (A), Walking (B), and LSR (C) categories during the full game for the NFL and AIC. Data are presented as mean with error bars representing SD and circles representing individual data points. NFL, National Football League; AIC, All-Ireland Championship.

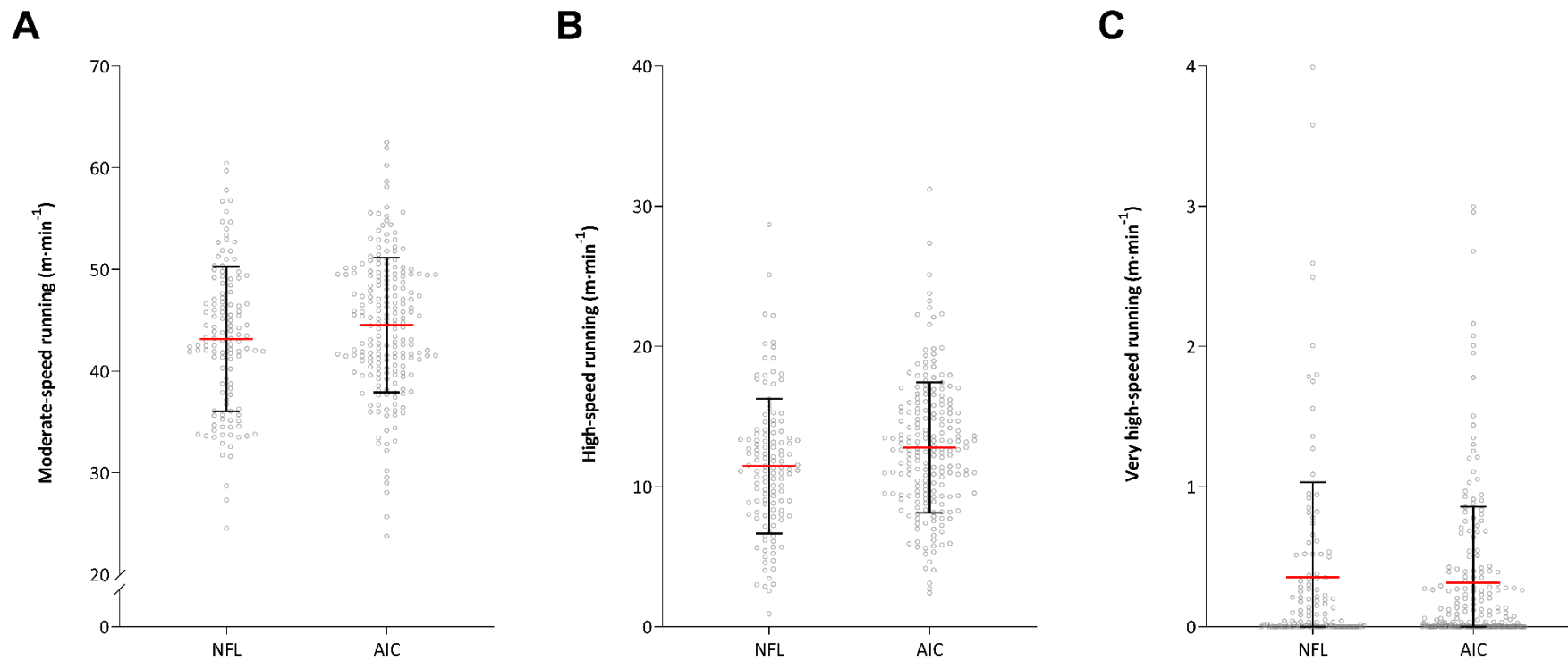


Figure 6.2. Relative distance in the MSR (A), HSR (B), and VHSR (C) categories during the full game for the NFL and AIC. Data are presented as mean with error bars representing SD and circles representing individual data points. NFL, National Football League; AIC, All-Ireland Championship.

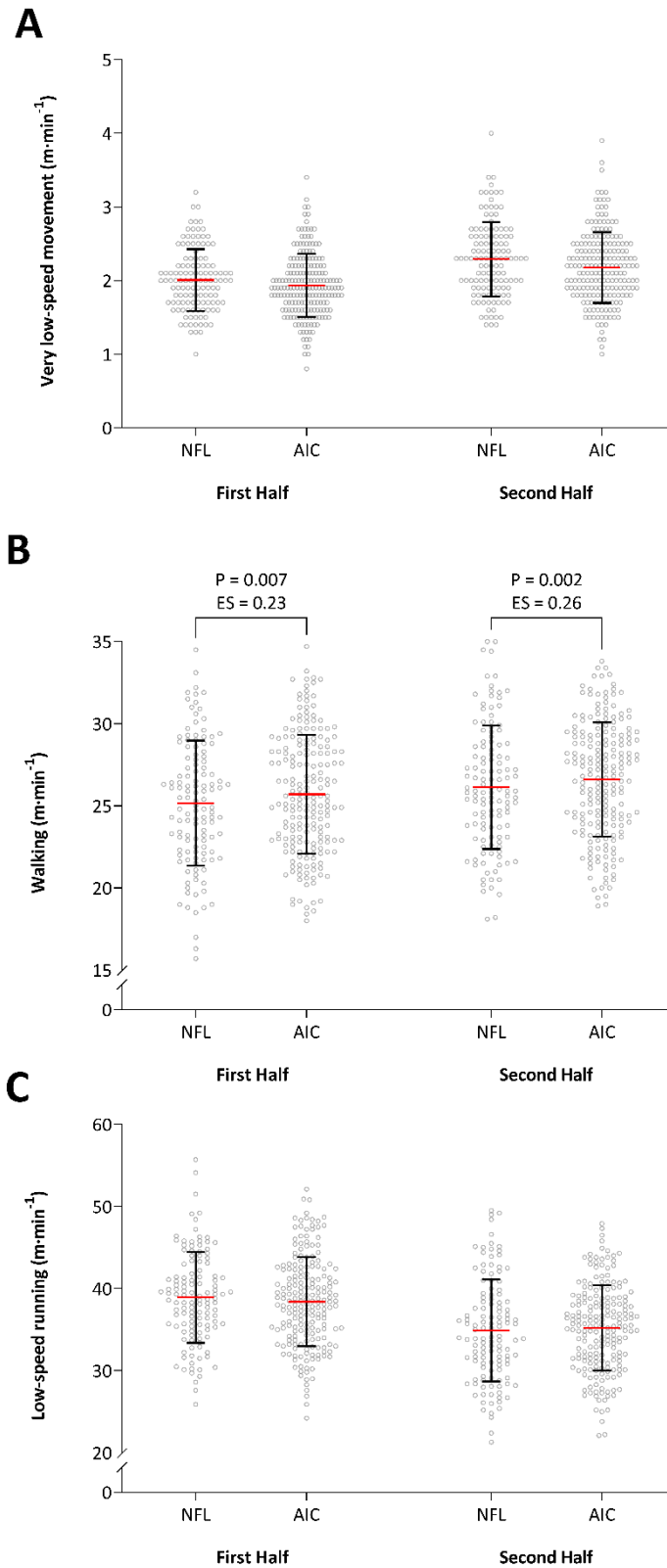


Figure 6.3. Relative distance in the VLSM (A), Walking (B), and LSR (C) categories during the first and second half of the NFL and AIC. Data are presented as mean with error bars representing SD and circles representing individual data points. NFL, National Football League; AIC, All-Ireland Championship.

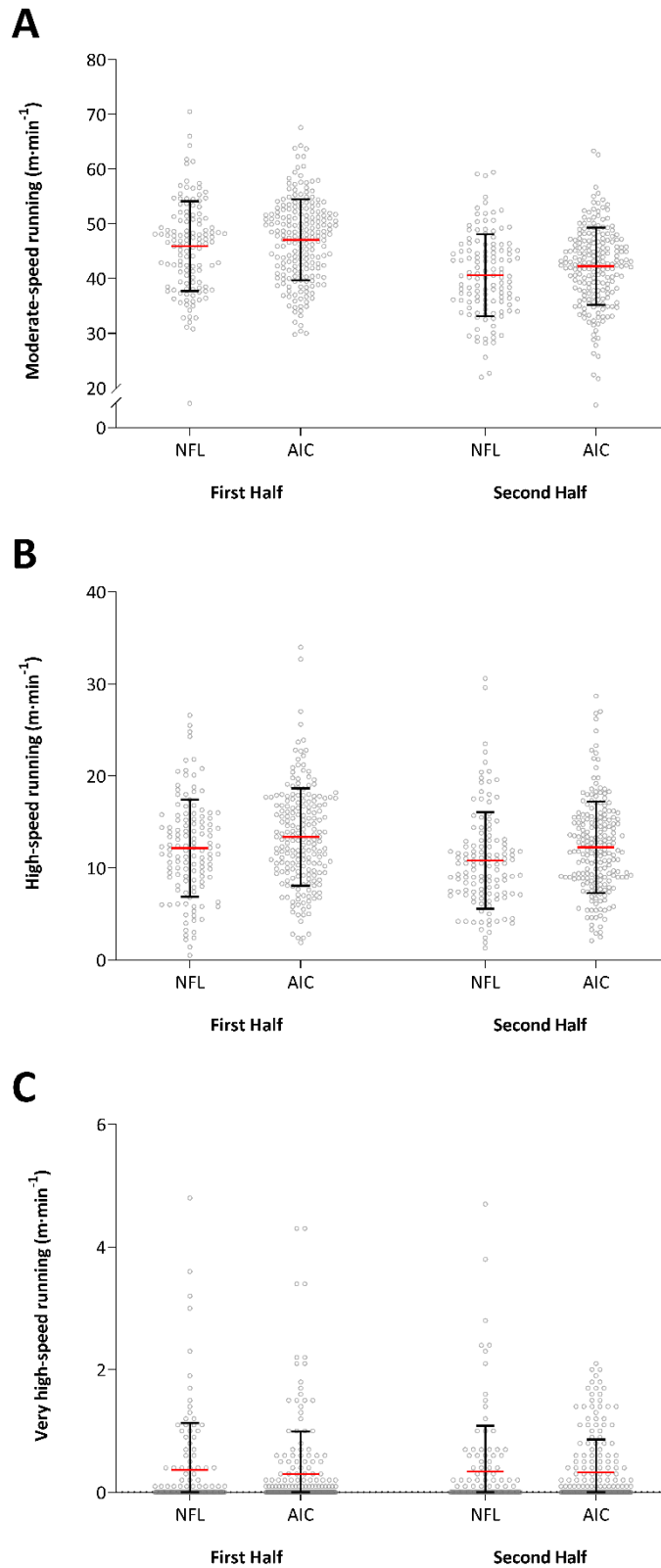


Figure 6.4. Relative distance in the MSR (A), HSR (B), and VHSR (C) categories during the first and second half of the NFL and AIC. Data are presented as mean with error bars representing SD and circles representing individual data points. NFL, National Football League; AIC, All-Ireland Championship.

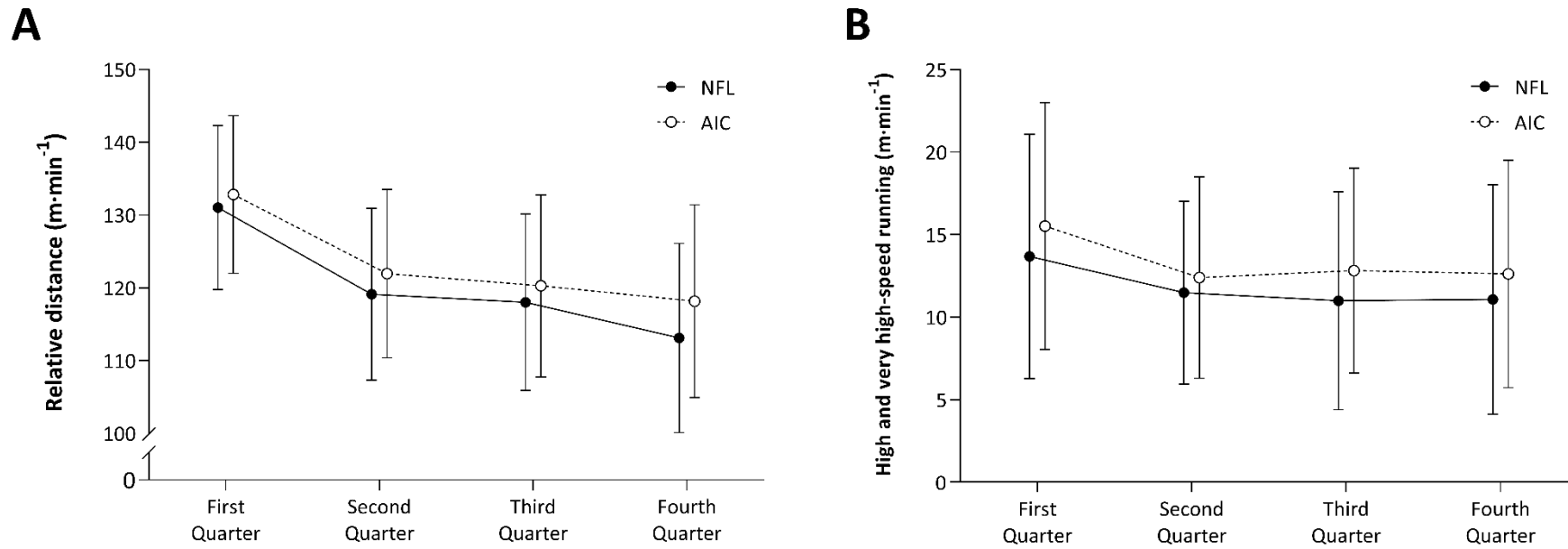


Figure 6.5. Relative distance (A) and the combined HSR and VHSR distance (B) across each quarter of match play during NFL and AIC games. Data are presented as mean values with error bars representing SD. NFL, National Football League; AIC, All-Ireland Championship.

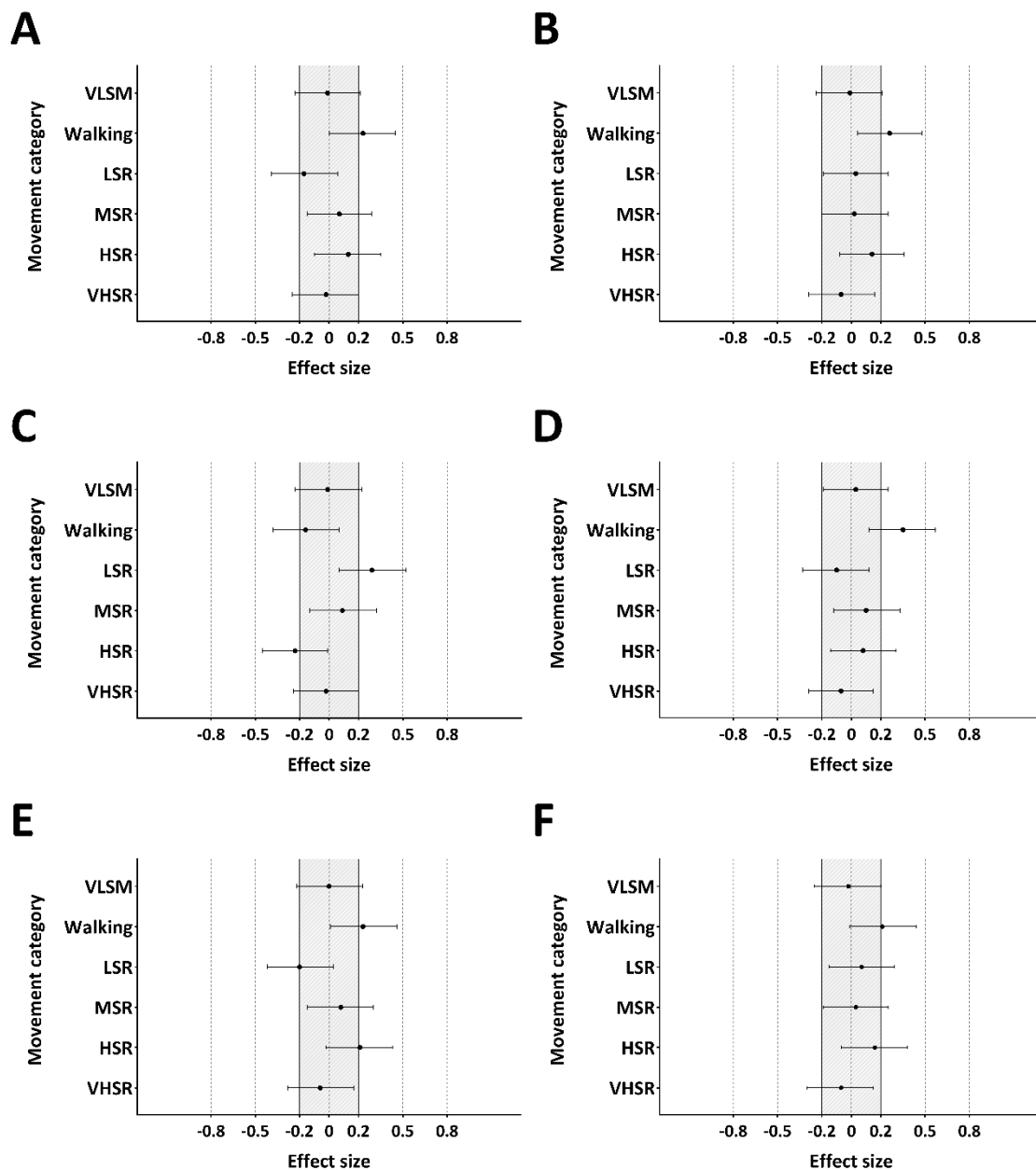


Figure 6.6. Effect size plots of the change in relative distance in each movement category between the NFL and AIC during the first half (A), second half (B), first quarter (C), second quarter (D), third quarter (E), and fourth quarter (F) of match play. Circles represent the ES, and the horizontal lines represent the 95% confidence interval. VLSM, very low-speed movement; LSR, low-speed running; MSR, moderate-speed running; HSR, high-speed running; VHSR, very high-speed running.

6.3.2 Ageing

6.3.2.1 NFL

There was no difference in the relative distance between the low (119.7 ± 2.4 m·min⁻¹), moderate (121.7 ± 2.3 m·min⁻¹), and high (117.6 ± 2.7 m·min⁻¹) age groups ($P = 0.469$, $ES = 0.23 - 0.46$) during NFL games. The relative distance in each movement category for each of the three age groups during NFL games is presented in Table [6.2](#). The relative distance in the LSR category was lower ($P = 0.037$, $ES = 0.96$) for the high age group compared to the moderate age group. There was no difference between the three age groups for relative distance in the VLMS ($P = 0.500$, $ES = 0.20 - 0.43$), walking ($P = 0.502$, $ES = 0.09 - 0.48$), MSR ($P = 0.732$, $ES = 0.04 - 0.22$), HSR ($P = 0.652$, $ES = 0.01 - 0.26$), or VHSR ($P = 0.150$, $ES = 0.00 - 0.46$) categories. Peak running speed was not different ($P = 0.623$, $ES = 0.11 - 0.31$) between the three age groups during NFL games.

6.3.2.2 AIC

There was no difference in the relative distance between the low (123.7 ± 1.8 m·min⁻¹), moderate (123.1 ± 1.5 m·min⁻¹), and high (123.1 ± 2.0 m·min⁻¹) age groups ($P = 0.956$, $ES = 0.00 - 0.07$) during AIC games. The relative distance in each movement category for the three age groups during AIC games is presented in Table [6.5](#). There was no difference between the three age groups for relative distance in the VLMS ($P = 0.572$, $ES = 0.11 - 0.26$), walking ($P = 0.502$, $ES = 0.00 - 0.21$), LSR ($P = 0.128$, $ES = 0.01 - 0.41$), MSR ($P = 0.562$, $ES = 0.01 - 0.19$), HSR ($P = 0.135$, $ES = 0.18 - 0.49$), or VHSR ($P = 0.968$, $ES = 0.03 - 0.08$) categories. Peak running speed was not different ($P = 0.623$, $ES = 0.15 - 0.33$) between the three age groups during AIC games.

6.3.3 Experience level

6.3.3.1 NFL

There was no difference in relative distance during NFL games between the low ($119.6 \pm 3.1 \text{ m}\cdot\text{min}^{-1}$), moderate ($120.1 \pm 2.0 \text{ m}\cdot\text{min}^{-1}$), and high ($119.2 \pm 3.4 \text{ m}\cdot\text{min}^{-1}$) NFL experience groups ($P = 0.976$, $ES = 0.05 - 0.09$) or between the low ($121.1 \pm 2.1 \text{ m}\cdot\text{min}^{-1}$), moderate ($119.3 \pm 2.8 \text{ m}\cdot\text{min}^{-1}$), and high ($118.5 \pm 2.1 \text{ m}\cdot\text{min}^{-1}$) AIC experience groups ($P = 0.720$, $ES = 0.09 - 0.29$) during NFL games. The relative distance in each movement category for the low, moderate, and high NFL and AIC experience groups during NFL games is presented in Table [6.3](#). The relative distance in the VHSR category was lower ($P = 0.021$, $ES = 0.85$) in the moderate group than the low group for AIC experience during NFL games. There was no difference between the three NFL experience groups for relative distance in the VLMS ($P = 0.262$, $ES = 0.39 - 0.91$), walking ($P = 0.178$, $ES = 0.28 - 0.89$), LSR ($P = 0.293$, $ES = 0.23 - 0.89$), MSR ($P = 0.827$, $ES = 0.05 - 0.22$), HSR ($P = 0.585$, $ES = 0.01 - 0.49$), or VHSR ($P = 0.894$, $ES = 0.03 - 0.22$) categories. There was no difference between the three AIC experience groups for relative distance in the VLMS ($P = 0.464$, $ES = 0.11 - 0.44$), walking ($P = 0.136$, $ES = 0.24 - 0.76$), LSR ($P = 0.627$, $ES = 0.12 - 0.27$), MSR ($P = 0.465$, $ES = 0.23 - 0.50$), or HSR ($P = 0.580$, $ES = 0.05 - 0.40$) categories. Peak running speed was not different between the three NFL ($P = 0.358$, $ES = 0.23 - 0.82$) or the three AIC ($P = 0.430$, $ES = 0.18 - 0.38$) experience groups during NFL games.

6.3.3.2 AIC

There was no difference in relative distance during AIC games between the low ($123.9 \pm 1.8 \text{ m}\cdot\text{min}^{-1}$), moderate ($122.1 \pm 1.6 \text{ m}\cdot\text{min}^{-1}$), and high ($123.9 \pm 2.2 \text{ m}\cdot\text{min}^{-1}$) NFL

experience groups ($P = 0.426$, $ES = 0.00 - 0.23$) or between the low ($126.0 \pm 1.8 \text{ m}\cdot\text{min}^{-1}$), moderate ($123.3 \pm 1.5 \text{ m}\cdot\text{min}^{-1}$), and high ($120.6 \pm 2.0 \text{ m}\cdot\text{min}^{-1}$) AIC experience groups ($P = 0.142$, $ES = 0.34 - 0.69$) during AIC games. The relative distance in each movement category for the low, moderate, and high NFL and AIC experience groups during AIC games is presented in Table [6.6](#). There was no difference between the three NFL experience groups for relative distance in the VLSM ($P = 0.597$, $ES = 0.07 - 0.28$), walking ($P = 0.063$, $ES = 0.18 - 0.53$), LSR ($P = 0.751$, $ES = 0.05 - 0.24$), MSR ($P = 0.374$, $ES = 0.04 - 0.24$), HSR ($P = 0.195$, $ES = 0.10 - 0.38$), or VHSR ($P = 0.224$, $ES = 0.02 - 0.36$) categories. There was no difference between the three AIC experience groups for relative distance in the VLSM ($P = 0.278$, $ES = 0.11 - 0.48$), walking ($P = 0.129$, $ES = 0.14 - 0.32$), LSR ($P = 0.185$, $ES = 0.10 - 0.42$), MSR ($P = 0.716$, $ES = 0.11 - 0.27$), HSR ($P = 0.182$, $ES = 0.32 - 0.65$), or VHSR ($P = 0.471$, $ES = 0.16 - 0.39$) categories. Peak running speed was not different between the three NFL ($P = 0.322$, $ES = 0.18 - 0.56$) or the three AIC ($P = 0.588$, $ES = 0.03 - 0.21$) experience groups during AIC games.

6.3.4 Aerobic fitness

6.3.4.1 NFL

There was no difference in the relative distance between the low ($116.9 \pm 1.9 \text{ m}\cdot\text{min}^{-1}$), moderate ($119.7 \pm 1.9 \text{ m}\cdot\text{min}^{-1}$), and high ($122.4 \pm 2.2 \text{ m}\cdot\text{min}^{-1}$) aerobic fitness groups ($P = 0.105$, $ES = 0.31 - 0.62$) during NFL games. The relative distance in each movement category for the three aerobic fitness groups during NFL games is presented in Table [6.4](#). The relative distance in the walking category for the low group was higher than both the moderate ($P = 0.006$, $ES = 0.60$) and high ($P = 0.015$, $ES = 0.83$) groups during NFL

games. There was no difference between the three groups for relative distance in the VLMS (P = 0.774, ES = 0.10 – 0.20), LSR (P = 0.062, ES = 0.12 – 0.55), MSR (P = 0.208, ES = 0.24 – 0.51), HSR (P = 0.491, ES = 0.16 – 0.34) or VHSR (P = 0.064, ES = 0.22 – 0.46) categories. Peak running speed was not different (P = 0.136, ES = 0.11 – 0.48) between the three aerobic fitness groups.

6.3.4.2 AIC

The relative distance in the low aerobic fitness group (120.5 ± 1.5 m·min⁻¹) was lower than both the moderate (124.5 ± 1.5 , P = 0.020, ES = 0.50) and high (124.9 ± 1.6 , P = 0.034, ES = 0.56) aerobic fitness groups during AIC games (Figure 6.7). There was no significant difference in relative distance between the high and moderate groups (ES = 0.06). The relative distance in each movement category for the three aerobic fitness groups during AIC games is presented in Table 6.7. The relative distance in the LSR category for the low group was lower (P = 0.005, ES = 0.42) than the moderate group. The relative distance in the HSR category was greater in the high aerobic fitness group than both the low (P = 0.003, ES = 0.74) and moderate (P = 0.008, ES = 0.58) aerobic fitness groups. There was no difference between the three groups for relative distance in the VLMS (P = 0.371, ES = 0.10 – 0.20), walking (P = 0.245, ES = 0.12 – 0.55), MSR (P = 0.314, ES = 0.24 – 0.51), or VHSR (P = 0.073, ES = 0.22 – 0.46) categories. Peak running speed was lower for the low aerobic fitness group than both the moderate (P = 0.001, ES = 0.62) and high (P = 0.001, ES = 0.76) aerobic fitness groups. There was no significant difference in peak running speed between the moderate and high aerobic fitness groups (ES = 0.14) during AIC games.

Table 6.2. Relative distance in each movement category for each age group during NFL games

	Low	Moderate	High
VLSM (m·min ⁻¹)	2.1 ± 0.1	2.1 ± 0.1	2.2 ± 0.1
Walking (m·min ⁻¹)	25.2 ± 0.9	25.6 ± 0.8	26.9 ± 1.0
LSR (m·min ⁻¹)	38.0 ± 1.4	39.5 ± 1.3	34.5 ± 1.5 ^a
MSR (m·min ⁻¹)	41.9 ± 1.9	43.5 ± 1.8	42.2 ± 2.1
HSR (m·min ⁻¹)	11.7 ± 1.2	10.5 ± 1.1	11.6 ± 1.4
VHSR (m·min ⁻¹)	0.5 ± 0.2	0.1 ± 0.2	0.1 ± 0.2

Data are presented as EMM ± SE. ^a P < 0.05 vs. Moderate. VLSM, very low-speed movement; LSR, low-speed running; MSR, moderate-speed running; HSR, high-speed running; VHSR, very high-speed running.

Table 6.3. Relative distance in each movement category for years of experience at national level and championship level during NFL games

	Experience Level	Low	Moderate	High
VLSM (m·min ⁻¹)	NFL	2.0 ± 0.1	2.1 ± 0.1	2.3 ± 0.1
	AIC	2.2 ± 0.1	2.1 ± 0.1	2.1 ± 0.1
Walking (m·min ⁻¹)	NFL	27.6 ± 1.1	25.5 ± 0.7	24.6 ± 1.3
	AIC	24.4 ± 0.8	27.0 ± 1.0	26.2 ± 0.8
LSR (m·min ⁻¹)	NFL	35.4 ± 1.8	36.6 ± 1.2	40.1 ± 2.0
	AIC	37.4 ± 1.2	38.0 ± 1.6	36.6 ± 1.3
MSR (m·min ⁻¹)	NFL	41.9 ± 1.9	43.5 ± 1.8	42.2 ± 2.1
	AIC	44.4 ± 1.7	40.8 ± 2.2	42.4 ± 1.7
HSR (m·min ⁻¹)	NFL	12.0 ± 1.6	12.0 ± 1.0	9.8 ± 1.8
	AIC	12.4 ± 1.1	10.6 ± 1.4	10.8 ± 1.1
VHSR (m·min ⁻¹)	NFL	0.3 ± 0.2	0.3 ± 0.2	0.1 ± 0.3
	AIC	0.6 ± 0.2	0.1 ± 0.2 ^a	0.2 ± 0.2

Data are presented as EMM ± SE. ^a P <0.05 vs. Low. VLSM, very low-speed movement; LSR, low-speed running; MSR, moderate-speed running; HSR, high-speed running; VHSR, very high-speed running. NFL, National Football League; AIC, All-Ireland Championship.

Table 6.4. Relative distance in each movement category for aerobic fitness during NFL games

	Low	Moderate	High
VLSM (m·min ⁻¹)	2.2 ± 0.1	2.1 ± 0.1	2.1 ± 0.1
Walking (m·min ⁻¹)	27.5 ± 0.7 ^{a,b}	25.5 ± 0.7	24.7 ± 0.8
LSR (m·min ⁻¹)	35.6 ± 1.1	37.9 ± 1.1	38.5 ± 1.3
MSR (m·min ⁻¹)	40.7 ± 1.5	42.4 ± 1.5	44.4 ± 1.8
HSR (m·min ⁻¹)	10.5 ± 1.0	11.3 ± 1.0	12.1 ± 1.2
VHSR (m·min ⁻¹)	0.2 ± 0.2	0.1 ± 0.1	0.4 ± 0.2

Data are presented as EMM ± SE. ^a P <0.01 vs. Moderate; ^b P <0.01 vs. High. VLSM, very low-speed movement; LSR, low-speed running; MSR, moderate-speed running; HSR, high-speed running; VHSR, very high-speed running.

Table 6.5. Relative distance in each movement category for each age group during AIC games

	Low	Moderate	High
VLSM (m·min ⁻¹)	2.1 ± 0.1	2.1 ± 0.1	2.0 ± 0.1
Walking (m·min ⁻¹)	25.4 ± 0.8	26.1 ± 0.7	26.0 ± 0.8
LSR (m·min ⁻¹)	36.3 ± 1.2	36.3 ± 1.1	38.4 ± 1.3
MSR (m·min ⁻¹)	45.5 ± 1.5	44.4 ± 1.2	45.5 ± 1.6
HSR (m·min ⁻¹)	13.2 ± 1.0	14.0 ± 0.8	11.9 ± 1.1
VHSR (m·min ⁻¹)	0.3 ± 0.1	0.3 ± 0.1	0.3 ± 0.1

Data are presented as EMM ± SE. VLSM, very low-speed movement; LSR, low-speed running; MSR, moderate-speed running; HSR, high-speed running; VHSR, very high-speed running.

Table 6.6. Relative distance in each movement category for years of experience at national level and championship level during AIC games

	Experience Level	Low	Moderate	High
VLSM (m·min ⁻¹)	NFL	2.0 ± 0.1	2.1 ± 0.1	2.1 ± 0.1
	AIC	2.0 ± 0.1	2.0 ± 0.1	2.2 ± 0.1
Walking (m·min ⁻¹)	NFL	26.0 ± 0.8	26.6 ± 0.7	24.9 ± 0.9
	AIC	25.4 ± 0.7	26.4 ± 0.7	25.8 ± 0.8
LSR (m·min ⁻¹)	NFL	36.5 ± 1.2	36.8 ± 1.1	37.7 ± 1.4
	AIC	38.3 ± 1.2	36.6 ± 1.0	36.1 ± 1.3
MSR (m·min ⁻¹)	NFL	45.7 ± 1.5	44.2 ± 1.3	45.5 ± 1.8
	AIC	46.0 ± 1.4	45.0 ± 1.2	44.4 ± 1.6
HSR (m·min ⁻¹)	NFL	13.3 ± 1.0	12.1 ± 0.9	13.7 ± 1.2
	AIC	14.4 ± 1.0	13.0 ± 0.8	11.6 ± 1.1
VHSR (m·min ⁻¹)	NFL	0.4 ± 0.1	0.2 ± 0.1	0.2 ± 0.2
	AIC	0.4 ± 0.1	0.3 ± 0.1	0.2 ± 0.1

Data are presented as EMM ± SE. VLSM, very low-speed movement; LSR, low-speed running; MSR, moderate-speed running; HSR, high-speed running; VHSR, very high-speed running. NFL, National Football League; AIC, All-Ireland Championship.

Table 6.7. Relative distance in each movement category for aerobic fitness during AIC games

	Low	Moderate	High
VLSM (m·min ⁻¹)	2.1 ± 0.1	2.0 ± 0.1	2.0 ± 0.1
Walking (m·min ⁻¹)	26.2 ± 0.7	25.4 ± 0.7	25.9 ± 0.7
LSR (m·min ⁻¹)	36.1 ± 1.1 ^a	38.3 ± 1.1	36.7 ± 1.1
MSR (m·min ⁻¹)	44.2 ± 1.2	45.9 ± 1.2	45.3 ± 1.3
HSR (m·min ⁻¹)	11.7 ± 0.8 ^b	12.4 ± 0.8 ^b	14.9 ± 0.9
VHSR (m·min ⁻¹)	0.2 ± 0.1	0.3 ± 0.1	0.4 ± 0.1

Data are presented as EMM ± SE. ^a P <0.01 vs. Moderate; ^b P <0.01 vs. High. VLSM, very low-speed movement; LSR, low-speed running; MSR, moderate-speed running; HSR, high-speed running; VHSR, very high-speed running.

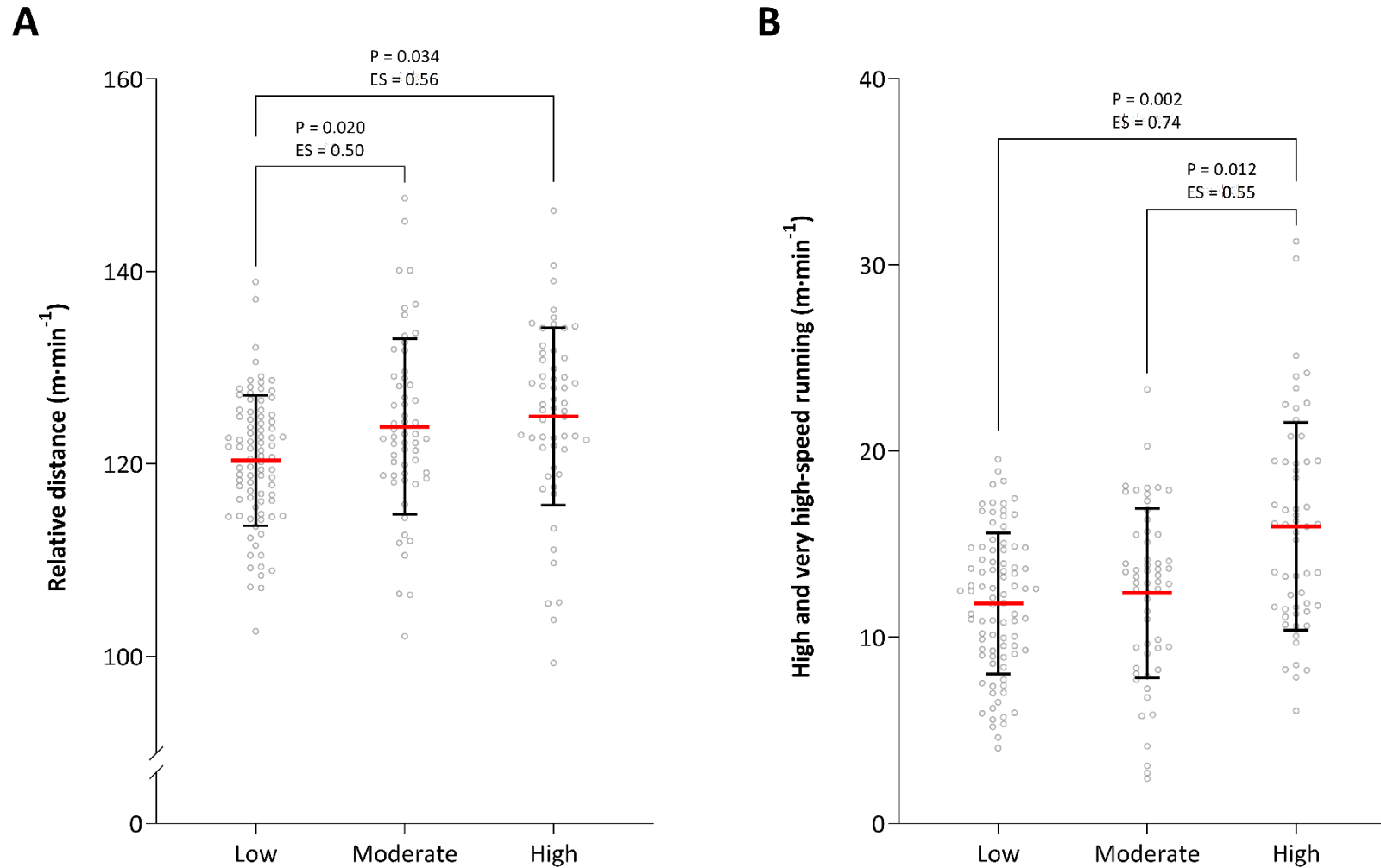


Figure 6.7. Relative distance (A) and the combined HSR and VHSR distance (B) for the low, moderate and high aerobic fitness groups during AIC games. Data are presented as mean with error bars representing SD and circles representing individual data points.

6.4 Summary

Games in the AIC were longer than in the NFL, due primarily to a longer second half. There was no difference in the relative distance covered during the full game, first half, second half, or in any of the four quarters between the NFL and AIC. Relative distance in the walking category was higher during the full game, first half, and second half of the AIC than the NFL. No differences were found in the VLMS, LSR, MSR, HSR, or VHSR categories or in peak running speed for the full game, first, or second half between the NFL and AIC. Only walking in the second quarter of the AIC and LSR in the first quarter of the NFL differed between competitions across the four quarters of match play.

There was no difference in the relative distance covered during the NFL or AIC between the low, moderate, and high age groups. The relative distance in the MSR, HSR, and VHSR categories and peak running speed was also similar between age groups in the NFL and AIC. There was no difference in the relative distance covered during the NFL or AIC between the low, moderate, and high NFL experience and AIC experience groups. During NFL games, VHSR was higher for the low NFL experience group than the moderate group. No other differences in the activity profile were found between the NFL experience groups or AIC experience groups during NFL games. During AIC games, no differences between NFL experience groups or AIC experience groups were found for the relative distance in any movement category or in peak running speed.

During NFL games, referees in the low aerobic fitness group covered more distance in the walking category than both the moderate and high aerobic fitness groups. However, there were no differences in any other movement category or in peak running speed

between groups. During AIC games, referees in the low aerobic fitness group covered a lower relative distance and had a lower peak running speed than both the moderate and high aerobic fitness groups. Referees in the high aerobic fitness group also covered a greater HSR distance than both the low and moderate groups.

CHAPTER VII

DISCUSSION

7.1 Discussion

7.1.1 Overview

Gaelic football is one of the most popular sports played in Ireland. At the elite level, games attract over 80,000 spectators with television audiences exceeding one million. While Gaelic football is lauded for its amateur status, the preparation of players in recent years has become increasingly similar to that of professional IFTS players (161). This shift towards a quasi-professional training regime is likely due in part to the increased understanding of the activity profile of the players during competitive match play, facilitated by significant advancements in GPS technology (8, 9). In contrast, there are currently no published studies examining the activity profile of elite GFR during match play despite the importance of their officiating role. Absence of activity profile data is a major limitation in the design and implementation of training practices specific to the physical requirements of elite GFR during match play.

A series of studies was undertaken to; i) generate movement category velocity thresholds specific to elite GFR, ii) describe the activity profile of elite GFR during NFL and AIC games, iii) examine the temporal changes and competitive level differences during games in the NFL and AIC and iv) examine the influence of age, refereeing experience, and aerobic fitness on the activity profile of elite GFR during games in both the NFL and AIC.

A number of studies have examined the activity profile of elite soccer and rugby referees during competitive match play. These studies have relied on arbitrary, player-based movement categories for their analysis which likely misrepresent the activity of the referee. A unique aspect of this study was the use of a two-stage unsupervised clustering technique to generate a set of six unique movement categories and their respective velocity thresholds for elite GFR. No previous studies involving IFTS referees have generated referee-specific movement category velocity thresholds. These newly generated movement categories were more strongly associated with the raw velocity data and resulted in significantly higher HSR and VHSR distances identified for elite GFR compared to arbitrary velocity thresholds that have been frequently used in previous studies analysing IFTS referees.

Application of these categories to activity data collected during NFL and AIC games provided a valuable insight into the activity profile of elite GFR during competitive inter-county match play. The current research has established that the full game activity profile of elite GFR is similar during NFL and AIC games. This was a surprising finding given the general perception that games in the AIC are of a higher playing intensity. In addition, the running performance of elite GFR was found to be reduced in the second half compared to the first half, with the first quarter often the most demanding period of the game during both the NFL and AIC. Examination of the differences between playing divisions of the NFL and the competitive phases of the AIC found few differences in the activity profile of elite GFR. This implies that competitive level has little influence on the activity profile of elite GFR during inter-county games.

The current research also highlights the limited influence of age and refereeing experience on the activity profile of elite GFR, in particular the total and HSR distance during NFL and AIC games. In contrast, aerobic fitness levels were found to influence the activity profile of elite GFR during inter-county games with referees who possessed higher aerobic fitness levels found to cover greater relative and HSR distances than referees with lower levels of aerobic fitness during AIC games. Overall, these findings will assist in developing conditioning programmes and better informing the selection criteria for elite GFR.

7.1.2 Velocity-based movement categories

Examination of the activity profile of IFTS players and referees typically involves partitioning the total distance covered during competitive match play into a number of velocity-based movement categories. This approach is used to gain a better understanding of the dynamic pattern of play during IFTS (6). The vast majority of research describing the activity profile of IFTS players and referees has used movement category velocity thresholds provided by the manufacturer of the respective tracking technology (120, 128, 151). Although no theoretical rationale or evidence justifying the selection of these arbitrary thresholds has been provided, they are routinely adopted in both applied and research settings (7, 57).

Recent studies examining the activity profile of IFTS athletes often cite consistency with prior research and/or the opportunity for inter-study comparison as justification for the use of arbitrary thresholds (11, 12, 107, 134). Notwithstanding the large number of published studies involving elite IFTS players and referees, there is currently no set of

standardised movement categories. At least three separate sets of arbitrary movement category velocity thresholds have been reported for Gaelic football (3, 8, 134). Similarly, several different sets of arbitrary movement category velocity thresholds have been used to describe the activity profile of elite IFTS referees both within and between sports, the majority of which were originally intended for use with elite male IFTS players (15, 59, 60, 114, 151). Ideally, movement category velocity thresholds should be specific to the cohort being examined to maximise both the internal and ecological validity of the results.

Unsupervised clustering techniques are becoming increasingly common in the analysis and discretisation of activity data (52, 94, 95). In the present study, a two-stage unsupervised clustering technique was undertaken to generate unique movement category velocity thresholds for elite GFR and to assess the utility of these thresholds. When using unsupervised clustering techniques, the number of thresholds or partitions within the dataset is specified in advance. Considering that an increase or decrease in the number of movement categories in a dataset will alter the dispersion of each velocity threshold, identifying the appropriate number of categories prior to generating the thresholds is of fundamental importance. To date, no study has examined the appropriate number of movement categories or provided rationale for the number selected (52, 94, 95).

The first stage of the unsupervised clustering technique in the present study involved the elbow method. This method is commonly used to assist in identifying the appropriate number of discrete movement categories within a dataset, and importantly limits the potential for error or bias (98). Five partitions were identified with the average

velocity at each partition subsequently forming the boundaries of six unique movement categories. This is similar to the number of arbitrary categories used previously to describe the activity profile of elite players and referees involved in IFTS (115, 127, 129, 134, 138). However, six movement categories may not be appropriate for all IFTS players and referees. The number of movement categories identified in the present study simply represents the appropriate number for the analysis of the data files collected from elite GFR during competitive match play. Future studies examining the activity profile of IFTS players or referees should incorporate the elbow method or a similar technique into their analysis to facilitate the selection of the appropriate number of movement categories. Adoption of this methodology by studies involving longitudinal datasets from the same cohort, sport, competitive level, etc., will enable meaningful comparison between studies and help to move towards a standardised approach for the analysis of the activity profile of IFTS players and referees.

One of the primary aims of discretisation is to identify partitions that minimise the loss of information (162). Previous studies that have generated unique sets of velocity thresholds have used differences in distance covered between the categories as evidence of their superiority and subsequent justification for their use in IFTS (52, 94). The failure of previous studies to objectively demonstrate a superior information gain is both a methodological and theoretical limitation to the use and generalisation of new velocity thresholds. A regression analysis was therefore undertaken on a subset of data files to compare the variation in the raw data accounted for between the newly generated velocity thresholds and a common set of arbitrary thresholds used in IFTS (60, 127, 127, 134, 138, 151). In all cases, the newly generated velocity thresholds accounted for a larger

amount of variance than the arbitrary thresholds. In essence, less information was lost using the newly generated velocity thresholds than the arbitrary thresholds, supporting the use of these thresholds in the analysis of activity data from elite GFR. While this approach may not always be suitable, such as when the number of categories is considerably different, given the similarities in the number of categories identified in the present study with previous studies involving other IFTS referees, the regression analysis presented an accessible and objective method to demonstrate the efficacy of the newly generated thresholds.

The spectral clustering technique partitioned the dataset at the points with the fewest traversals between velocities, known as the minimum cut problem (52). These categories represent the most naturally occurring movement speeds of elite GFR during match play. With the exception of the VLMS category, all velocity thresholds were between 0.3 – 0.7 m·s⁻¹ lower than the corresponding arbitrary velocity thresholds that have been applied extensively to elite IFTS players and referees (60, 127, 127, 134, 138, 151). In particular, the newly generated HSR and VHSR thresholds generated were ~0.6 m·s⁻¹ and ~0.5 m·s⁻¹ lower than the arbitrary HSR (5.5 m·s⁻¹) and sprinting (7.0 m·s⁻¹) thresholds, respectively. The lower thresholds for elite GFR may reflect differences in age and physical capacity between elite players and referees (18, 146, 149). Indeed, GFR in the present study were on average 15 years older than elite Gaelic football players (8, 134). However, the velocity thresholds commonly used in the analysis of elite IFTS players and referees are merely arbitrary and are assigned independent of the physical capacity of the cohorts for which they were first used (120, 128, 151). Applying unsupervised clustering with activity data from elite Gaelic football players during inter-county games,

and undertaking direct comparisons of the physical capacity of elite GFR and players will help to better understand the differences in velocity thresholds.

The combined total distance covered by elite GFR in the two highest movement categories commonly used in previous studies analysing the activity profile of IFTS referees ($\geq 5.5 \text{ m}\cdot\text{s}^{-1}$) was 321 m. In contrast, the combined total distance covered by elite GFR in the two highest velocity movement categories in the present study, HSR and VHSR, was 966 m. This equates to an increase of 645 m or 201%. Application of the arbitrary thresholds to the activity data of elite GFR would have largely underestimated the volume of HSR and VHSR. The lack of exposure to sufficient volumes of HSR and VHSR in training may not provide a sufficient training stimulus. In contrast, the improved understanding of the volume of HSR and VHSR performed by elite GFR during match play will assist in the prescription of a more optimal training dose. This is important to ensure GFR are optimally prepared for the HSR and VHSR periods that occur during match play (163, 164). Regular HSR and VHSR exposure in training is also associated with a reduced risk of lower-limb injuries (165), which are the most common injury type among GFR (166).

Recently, a number of studies have adopted velocity thresholds derived using the unsupervised clustering techniques (167–169). However, there is still no consensus regarding the appropriateness of the unsupervised clustering techniques for generating velocity thresholds (170, 171). Indeed, others strongly recommend the use of physiological thresholds or physical performance indicators to anchor velocity thresholds in IFTS (81, 82, 89). Movement category velocity thresholds based on physiological measures typically use the speed at a threshold such as VT, RCP or FBLC to demarcate

entry into a particular category. This approach has been used to derive both individual and group-based movement categories thought to be reflective of the relative intensity of exercise during IFTS (79, 82). Application of physiological thresholds in this way ignores the fact that they are representative of a metabolic rate, above which a particular physiological response occurs. These thresholds are also typically determined in a laboratory setting using controlled increments in workload. In addition, there is limited evidence to support the use of thresholds based on the speed at VT, RCP or FBLC to demarcate transitions between the exercise intensity domains (61). This approach is an oversimplification of the distinct metabolic and ventilatory responses associated with these thresholds and is further compounded by the lack of research examining the relation with blood lactate and $\dot{V}O_2$ kinetics during IFTS (56).

An example of the misapplication of physiological measures is evident in the recent analysis of a Gaelic football player where a movement category termed 'conditioning distance' with a velocity threshold of $\geq 4.47 \text{ m}\cdot\text{s}^{-1}$ was reported (172). This threshold is seemingly based on the arbitrary value previously used to determine running economy (RE) for a cohort of Gaelic football players (173). This value ignores the basic definition of RE which is the $\dot{V}O_2$ at a given velocity, that requires a physiological steady state and is typically expressed as the volume of oxygen required to run 1 km relative to body mass (174, 175). How this value relates to the intermittent pattern of play or provides a greater insight into the rigors of match play during IFTS is unclear.

A number of limitations also exist for the use of physical performance indicators such as MSS or MAS to form group-based and/or individual-specific movement category

velocity thresholds. The MSS provides an insight into the upper limit that can be achieved by an individual. However, movement categories based on this metric alone require the use of arbitrary cut points for which there is no agreement in the scientific literature. There is also no standardised approach to determine MSS. Similarly, MAS can be estimated using a variety of field-based fitness tests, many of which involve corrective equations that can introduce error (151, 176, 177). The MAS is also impacted by the testing protocol used for its determination which can result in different values being recorded (178). Most importantly, neither MSS or MAS are reflective of the relative intensity of exercise and should not be used to make inferences regarding the volume of work performed in each exercise intensity domain. They simply represent the result of a particular test with no evidence demonstrating their superiority over traditional arbitrary categories.

The lack of scientific rigour regarding the use of physiological thresholds and physical performance indicators to demarcate velocity thresholds has led to confusion in the scientific literature and has made it virtually impossible to draw meaningful comparisons between studies. The unsupervised clustering technique in the present study provides a viable alternative to the use of arbitrary movement categories and physiological or performance metrics. This approach permits the formation of both individual and group-based categories. It eliminates the need for dedicated exercise testing sessions, is based on the activity data of the population being monitored, provides an assessment of the number and strength of the velocity thresholds, and can be updated as often as required.

In an effort to provide context to each of the newly generated movement category velocity thresholds, the verbal descriptors VSLM, walking, LSR, MSR, HSR and VHSR were assigned. The use of the term speed was preferred over intensity in the present study. The use of the term 'intensity', although widely used when describing arbitrary velocity thresholds in IFTS (14, 15, 60, 105, 106, 125, 131), is problematic. This is due to the fact that they are not based on the relative intensity of exercise, which is recognised as having three distinct domains, termed moderate, heavy and severe, each with distinct blood lactate and $\dot{V}O_2$ kinetics (61–63). Equally, studies involving the use of physiological thresholds, for example the RCP, or physical performance indicators, such as MSS, to generate velocity thresholds that are not recognised as being able to distinguish between the exercise intensity domains should avoid using the term intensity. The descriptor speed represents a suitable alternative to intensity as it avoids possible misinterpretation of the meaning of the data.

The verbal descriptors for each of the newly generated velocity thresholds were chosen to demonstrate the progressive increase in movement speed, ranging from VLSM to VHSR. The use of verbal descriptors in this way provides a useful way for practitioners to deliver feedback to other members of the coaching staff and to the athletes. The highest velocity threshold used previously to examine IFTS referees has often been termed sprinting (14, 15, 59, 60, 116, 124, 125, 127). As there is currently no consensus regarding the velocity threshold for sprinting among athletes participating in IFTS (179), VHSR was used to denote the highest movement category for elite GFR. Although verbal descriptors can be useful for practitioners when delivering feedback to coaching staff, referees and players, they are for the most part applied subjectively (180). Similar to velocity

thresholds, there is currently no consensus on the most appropriate verbal descriptors to use when examining activity data. To avoid adding further confusion when interpreting and applying movement category velocity thresholds, an appropriate strategy may be to report the data independent of verbal descriptors.

7.1.3 Activity profile of elite GFR

During NFL and AIC games, elite GFR covered 119.6 m·min⁻¹ and 122.6 m·min⁻¹, respectively. This distance is ~3 – 6% greater than the mean relative distance reported for elite Gaelic football players during NFL and AIC games (8). This difference may be due in part to the fact that GFR are required to keep up with play at all times, independent of game tempo whereas players have specific positional roles with brief and intense periods of movement followed by periods of low speed activity (8, 134). In the present study, additional time at the end of each half was included in the analysis as it can represent a significant portion of the playing time. In the only published study to report relative distance of elite Gaelic football players during NFL and AIC games (8), the analysis simply divided the total distance, inclusive of additional time, by the arbitrary game duration of 70 min (137). Therefore the difference in relative distance between elite GFR and players during inter-county games may actually be larger than reported.

The relative distance covered by elite GFR is considerably larger than reported for both elite rugby league (127, 129), and rugby union referees (122, 124), and similar to elite soccer referees (13). In addition to the differences in pitch size, the lower relative distance of elite rugby referees is likely due to the numerous collisions, ground contacts, scrummages etc., that slow the pattern of play and subsequently reduce activity levels

(129). In contrast, the more dynamic pattern of play in Gaelic football and soccer likely requires greater activity by the referee. In soccer, scores accrue entirely from goals. Approximately 85% of the goals are scored from inside the penalty area with ~25% of these occurring inside the 'six-yard' box (181). In Gaelic football where players can score goals or points by striking the ball off the ground or from their hand, the average distance from the goal is 31 m for each scoring attempt (182). This likely reduces the area that GFR need to cover during a game, resulting in a similar distance covered to soccer referees, despite the much larger playing area.

Similar to soccer and rugby referees, the majority of the total distance covered by elite GFR during competitive match play during both NFL and AIC games was completed at low and moderate speeds (13, 54, 129). The HSR and VHSR distance covered equated to ~10% of the total distance, reflective of the intermittent nature of Gaelic football. Comparisons between other studies for the HSR and VHSR distances are difficult due to differences in data collection methodologies and movement category velocity thresholds. Unlike previous studies that have used arbitrary or player-based thresholds to evaluate the activity profile of soccer and rugby referees, the velocity thresholds used in the present study were developed specifically for GFR and therefore provide greater internal validity.

The proprietary GPS/GNSS software provided information on the number of HSR and VHSR bouts and the distance of each bout performed by elite GFR during NFL and AIC games. However, accurate quantification of the HSR and VHSR bouts is difficult due to the oscillations which occur in the raw data, the lack of information provided by the GPS/GNSS manufacturer on the pre-processing filtering algorithms applied to activity data and the

lack of standardisation around the classification of a HSR or VHSR bout (179). Oscillations in the instantaneous velocity frequently occur in the raw velocity data. These oscillations may cause the speed during a HSR or VHSR bout to dip below the particular threshold for a brief moment, signalling the end of that bout. While GPS/GNSS manufacturers likely filter out these oscillations, analysis of the HSR and VHSR bouts using the raw data would result in separate bouts being recorded unless additional criteria was applied, e.g., termination of the HSR or VHSR bout only when a particular speed is reached. Analysis of the HSR and VHSR bouts from the raw GPS/GNSS activity data would likely provide a false narrative regarding the activity profile of elite GFR and therefore was omitted from the analysis in the present study.

Although the intensity of match play is thought to be greater during the AIC than the NFL due to teams prioritising the AIC (11), findings of the present study do not support this assumption for elite GFR. Games in the AIC were longer in duration than in the NFL but the relative distance between competitions was not significantly different, varying by only 3.0 m·min⁻¹ or 2.5%. There were also no differences found for VLMS, LSR, MSR, HSR, and VHSR distance or peak running speed between the NFL and AIC. The HSR distance accounted for 9.6% and 10.4% of the total distance during NFL and AIC games, respectively. To date, no published studies have directly examined the differences in activity profile of elite Gaelic football players between the NFL and AIC. Given the direct relation of the activity profile of the referee with the players in soccer (60), between competition examinations of the activity profile of elite Gaelic football players would better inform the findings of the present study. Indeed, no difference in the HSR distance (≥ 4.72 m·s⁻¹) of elite players was found between the national leagues and AIC in hurling

which is a native Irish sport that shares a number of similarities with Gaelic football including the competition structure, playing area and team formations (183).

Given the strong relation between both the total and HSR distance ($>5.5 \text{ m}\cdot\text{s}^{-1}$) covered by elite soccer referees with that of the players, it has been recommended that the activity profile of IFTS referees be examined alongside the players to gauge the overall game intensity (60). However, previous studies examining the activity profile of IFTS referees and players concurrently have involved the use of CBT (60, 106). Currently, CBT systems are not available in any Gaelic football stadium. Instead, analysis of the activity profile of both the referee and players is reliant on GPS technology for which no data sharing agreement currently exists between parties. In addition, teams may use GPS units from a number of different manufactures or may choose not to use any player tracking technology. Comparison of the activity profile of elite GFR with Gaelic football players at this time is therefore limited to published studies.

The present study compared the activity profile of elite GFR between the three phases of the AIC (AIQ, provincial championships, AIS) and between the four divisions of the NFL to provide a more in-depth understanding of the differences between competitions. No studies have examined differences in the activity profile of elite Gaelic football players between the three phases of the AIC or across the four divisions of the NFL. The full game duration in the AIS was 2% longer than in the provincial championships, but no differences were found between either the AIS or the provincial championships and the AIQ. There was also no difference in relative distance between the three phases of the AIC. Indeed, the relative distance differed by only 0.6 – 1.4% between the three

phases. There was also no difference between phases for HSR distance, which accounted for 10.2%, 10.8% and 10.2% of the total distance covered during the AIQ, provincial championships and AIS, respectively. The only difference in the activity profile of elite GFR was in the LSR movement category, in which a greater distance was covered during games in the AIS than both the AIQ and provincial championships. Similarly, there was no significant difference in mean game duration, relative distance, distance covered in each movement category or the peak running speed between the four divisions of the NFL. Relative distance differed between the four divisions by 0.3 – 2.0% with HSR accounting for 8.5 – 11.6% of the total distance covered. Interestingly, HSR accounted for the lowest percentage of the total distance during Division 1 games (8.5%), and the highest percentage during Division 4 games (11.6%).

The similarities in activity profile between the AIQ, provincial championships and AIS in the present study may be a consequence of the 'knock-out' competition format in the AIC. Compared to a round robin format such as that in the NFL where a number of games can be considered unimportant, meaning that the game does not influence the outcome of the competition or cannot impact final team ranking (184), during a 'knock-out' format all games are given the highest priority. This difference in competition structure did not however translate into a difference in the activity profile of elite GFR between the NFL and AIC. The addition of the Super 8's format to the AIS in 2018 resulted in the introduction of a small number of round-robin style games into the AIC. However, the limited number of games makes it difficult to quantify the effect, if any, on the activity profile of elite GFR. The Super 8's was implemented on a trial basis and will not be part of future seasons with the AIC reverting to a 'knock-out' only format.

Although non-significant, the greater HSR distance during games in Division 4 may be due in part to teams in the lower tiers prioritising the NFL over the AIC given that they are rarely competitive in the AIC. Indeed, no team from Division 4 and only three teams from Division 3 reached the AIS during the observation period in the present study and have not progressed beyond the semi-finals. Equally, the lowest volume of HSR was performed by elite GFR during Division 1 games but this was also not significantly different to the other divisions. It is difficult to add merit to this observation given the non-significant differences, the relatively small number of games in each division, the large variation in HSR of elite GFR, and the lack of the corresponding player dataset to confirm the varying levels of activity.

These findings are different to previous studies that found elite Gaelic football players covered a greater total and HSR distance ($\geq 4.72 \text{ m}\cdot\text{s}^{-1}$) during the latter stages of the AIC (11) and that the high-speed activities of a Division 3 team were greater than a Division 1 team by up to 19% (12). However, a number of methodological limitations of these studies makes it difficult to make meaningful comparisons. Firstly, the studies reporting greater HSR by elite Gaelic football players during the latter months of the playing season and between playing divisions have used GPS units sampling at 4 Hz. The intra-unit reliability for HSR of these units has a CV of 8% (11, 12). Secondly, both studies reported distance in absolute terms. No information was provided on the inclusion or exclusion of additional time at the end of each half which as previously stated, can differ between phases of the AIC. Thirdly, despite these studies including multiple observations per team and per player, the statistical approaches used did not control for the non-independence of observations which can increase the risk of type 1 error (185, 186). Data

files included in the analysis of seasonal variations were also collected during different seasons (2012 – 2016) than the present study and provide no contextual information other than month of the season (11). No information on the data collection period was provided in the study examining the effect of divisional status on the activity profile of elite Gaelic football players (12). Nonetheless, the findings of the present study have important practical consequences, highlighting the consistent levels of activity required by elite GFR throughout the entirety of the NFL and AIC, regardless of playing division or championship phase. Although the dataset in the present study is extremely robust, comprising the entire panel of elite GFR across four competitive seasons, every level of the two major competitions played annually and involve all eligible teams, the large game to game variation in HSR must also be considered when interpreting the between-competition differences and evaluating the activity profile of elite GFR for the development of conditioning programmes.

In the present study, there was a 7.5% and 6.3% reduction in relative distance between halves during NFL and AIC games, respectively. With the exception of VHRS, the distance covered in each movement category was also different between halves during games in both the NFL and AIC. Similar between-half differences have been reported for elite Gaelic football players (8) and elite soccer referees (58, 106). The second half of both NFL and AIC games was longer than the first half which was likely caused by the increased number of stoppages due to injuries (187) and substitutions that typically occur during the latter part of IFTS, and may have contributed to the reduction in running performance (188). The absence of ball in play data to confirm the greater number of stoppages does represent a limitation of the present study and should be given due consideration when

interpreting the findings of the present study. Reductions in the activity of referees, in particular a decrease in the total distance and high-speed activities between match periods have previously been used to identify the presence of fatigue during IFTS (14). However, as the majority of the distance covered by elite IFTS referees is at low and moderate speeds, HSR is considered to be a better indicator of fatigue than total distance but is prone to large between match variation of ~25% and should be interpreted carefully (106, 107).

The HSR distance of elite GFR was 11.5% and 8.2% lower in the second half than the first of NFL and AIC games, respectively. However, no differences were found between the second, third, and fourth quarters of match play in either competition. In addition to the increased number of stoppages in the second half, the reduction in HSR distance may partly be explained by the intense first quarter of match play. During the first quarter of NFL games, elite GFR covered a greater total, LSR, and MSR distance and less distance in the VLMSM and walking category compared to any other quarter. In addition, a greater HSR distance was covered during the first quarter than the third and fourth quarter of NFL games. During the first quarter of AIC games, a greater total, LSR, MSR, and HSR distance and lower walking distance was covered compared to any other quarter. The VLMSM distance was also lower in the first quarter than the third and fourth quarter of AIC games. A similar pattern has been reported for referees of other IFTS (105, 124). The intense first period of match play in IFTS may be due to players trying to impose themselves both individually and collectively on the opposition (55).

The total distance and high-speed activity of elite soccer referees is directly related to that of the players (60), which is in turn influenced by the technical and tactical approach of their respective team (155). Examinations of the temporal changes in activity profile of elite Gaelic football players during NFL and AIC games found a time-dependant reduction in total, HSR ($\geq 4.72 \text{ m}\cdot\text{s}^{-1}$) and sprint distance ($\geq 6.11 \text{ m}\cdot\text{s}^{-1}$) with an ~8 – 18% greater HSR distance in the first quarter than in any other quarter (9). The broadly similar temporal changes in activity of elite GFR and elite players, coupled with the absence of a reduction in HSR between the second, third, and fourth quarters of match play make it difficult to discern the extent to which elite GFR experience fatigue during inter-county games in the NFL and AIC.

It has been speculated that IFTS referees employ a 'pacing strategy' to maintain the necessary running performance in the latter stages of a game (13). However, given the unpredictable nature of match play in Gaelic football it is unclear to what extent the referee can choose to pace their activities. When making comparisons between the activity profile of Gaelic football players and referees, it is important to consider that unlike referees, players experience considerable physical contact that may increase physical fatigue and contribute to the differences in activity profile (134). Players can also be substituted in response to a significant decline in their physical performance, while GFR must be able to maintain the required activity levels for the duration of the game. This requires that elite GFR possess the necessary fitness levels to keep up with play, irrespective of the game tempo or period.

7.1.4 Influence of contextual factors

Elite GFR in the present study were on average 15 years older than elite inter-county Gaelic football players (8, 134). This difference may be due to the fact that elite GFR spend a considerable number of years officiating at the sub-elite level prior to being selected for the national panel and the fact that many referees begin their career much later in life, usually after playing Gaelic football for a number of years. The age of elite GFR is an important consideration due to age-related declines in physical fitness that include reductions in muscle mass and strength and a decrease in $\dot{V}O_{2max}$ (147). The decline in physical fitness with ageing may compromise the ability of elite GFR to keep up with play. Despite no research examining the impact of ageing on elite GFR, the GAA impose a mandatory retirement age of 50 years at national level. In soccer, where many elite referees are professional, similar restrictions were in place but have been successfully challenged in some countries for violating employment laws (142). This does not apply to elite GFR due to the amateur status of the GAA.

Examination of the difference in the activity profile across age groups in the present study found that with the exception of LSR between the 'moderate' and 'high' age groups during NFL games, there was no difference between the three groups for relative distance, distance covered in each movement category or peak running speed during NFL or AIC games. The lack of difference between age groups may be partly explained by the fact that elite GFR must possess a minimum level of fitness prior to officiating NFL and AIC games. This requires regular training at a range of running speeds that may help to mitigate the age-related decline in physical fitness (189, 190). It is also unlikely that the

activity profile of elite GFR during competitive games reflects the maximal work rate of the referees given that the majority of the distance is covered at low and moderate speeds. The findings of the present study are in contrast to the only other study examining the influence of age on the activity profile of elite IFTS, where a significant age-related decline in the total and HSR distance ($>5.5 \text{ m}\cdot\text{s}^{-1}$) of elite soccer referees was found (142). While direct comparisons are difficult, differences may be due to the different age range, HSR threshold, game duration and statistical approach.

Despite the lack of difference between age groups in the present study, it is not possible to evaluate the utility of the mandatory retirement age. By implementing these restrictions prior to examining the differences between referees who are both older and younger than 50 years of age, the age limit in itself, has prevented meaningful examination. It is interesting to note that during the 709 inter-county games in the NFL and AIC between 2016 and 2019 only 50 (7.1%) were officiated by a referee over the age of 45. Further, only 12 games (1.7%) were officiated by a referee aged 49 or 50. The reason for the limited number of referees officiating up to the mandatory retirement age is unknown but given the lack of officials reaching this limit, it may be obsolete. To enhance the long-term recruitment and retention of elite GFR, a more appropriate solution than a blanket retirement age may be to allow referees who wish to continue officiating at national level beyond the age of 50 years to apply for a yearly extension. The extension could be based on the individual's ability to achieve the required minimum fitness standard each year, to maintain the necessary levels of activity during games, and to officiate at the required standard during the previous season.

Examination of refereeing experience in the present study yielded similar results to age. Except for VHSR between the 'low' and 'moderate' AIC experience groups during NFL games, there was no between-group difference in relative distance, distance covered in each movement category or peak running speed during NFL or AIC games. This finding was not unexpected, given the size of the playing area in Gaelic football and the requirement for elite GFR to keep up with play at all times. In addition, years of experience was found to have no effect on the activity profile of elite soccer referees, with both 'high' and 'low' experience referees demonstrating similar levels of between-match variation (107, 110).

In the present study, years officiating in the NFL and years officiating in the AIC were classified separately. This was deemed necessary as games in the AIC are of greater importance and are officiated by a select panel of referees chosen on a yearly basis from the NFL panel. Classification of experience based on years alone may be an oversimplification of what refereeing experience truly entails. For example, years' experience alone does not account for the standard of games officiated or indeed the overall performance of the referee. While it is plausible that a greater experience level may enhance the ability of the referee to maintain the necessary proximity to play and to select the optimal viewing angle for decision making, this information likely cannot be captured by reduced activity alone. Examination of the effect of experience level on the activity of elite IFTS referees in future studies should endeavour to form a more holistic understanding of experience level. This may include the development of a ranking system for the standard of games officiated, objective information on the accuracy of decisions, and analysis of the position of the referee during match play.

A high level of physical fitness is widely recognised as a prerequisite for refereeing at the elite level of IFTS (191). To be eligible to officiate NFL and AIC games, GFR are required to cover a minimum of 1,400 m and 1,560 m, respectively in the YIRT1. The difference in standard between the NFL and AIC exists based on the assumption that the intensity of match play is greater during AIC games than NFL games. As previously discussed, this is not supported by the findings in the present study. However, games in the AIC take place during the summer months with higher ambient temperatures than games in the NFL that are played primarily during the winter months. Exercise in the heat can place additional physiological stress on GFR, such as an elevated heart rate, reduced blood flow to exercising muscles, increased sweat rate and dehydration (192, 193). Indeed, the effects of high ambient temperatures on physiological function can be considerable given that the summer temperature in Ireland can vary by 15 – 20°C in a very short period, providing little or no time for acclimatisation. The increased physiological stress can impact both physical and cognitive performance (192, 193). Additionally, in the event of a draw following an AIC game, but not an NFL game, two 10 min periods of extra-time are typically played. The current higher minimum standard in the YIRT1 for AIC games may therefore be warranted.

Using the fitness level of the referee, based on their performance in the YIRT1 prior to the NFL and AIC each year, both NFL and AIC games were classified as either 'low', 'moderate' or 'high'. The relative distance covered by elite GFR during 'moderate' and 'high' AIC games was 3 – 4% greater than during 'low' games. The HSR distance was also greater during 'high' AIC games than during 'moderate' and 'low' games by 17% and 22%, respectively. In contrast, no differences in total or HSR distance were found between

'low', 'moderate' and 'high' NFL games. While the lack of difference between the 'low', 'moderate' and 'high' NFL games is somewhat surprising, this may be due to a number of factors. Firstly, the minimum fitness standard required to officiate NFL games is lower than AIC games. This resulted in a number of differences in the fitness levels within each group between the NFL and AIC. For example, the 'high' category for NFL games encompasses the entire 'moderate' AIC category. Secondly, while all referees were directed to continue beyond the minimum fitness standard when performing the YIRT1, it is difficult to confirm that all referees continued until volitional exhaustion. Thirdly, physical fitness levels can vary throughout the playing season (88). Elite GFR who are likely to be selected to officiate in the AIC will likely be motivated to continue training throughout the NFL to achieve the higher minimum standard. In contrast, referees who are unlikely to be selected for the AIC panel may not engage in exercise training at the same frequency or intensity. It is difficult to measure this variation during the NFL as the scheduling of games and travel arrangements limit the in-season testing opportunities. Therefore it is possible, that differences in aerobic fitness levels may influence the activity profile of elite GFR during NFL games.

A significant relation between YIRT1 performance and both total and HSR distance has been reported for elite soccer referees (14, 119). Interestingly, among elite soccer referees, an improvement in YIRT1 performance following a short-term exercise programme increased the volume of HIR ($>15 \text{ km}\cdot\text{h}^{-1}$) performed during games and reduced the distance from infringements, particularly during the last 30 min of match play (14). It is difficult to make comparisons with the performance of elite GFR as only the percentage change in YIRT1 performance for these elite soccer referees was provided (14).

The absence of a control group also makes it difficult to generalise these findings given that the movement of the referee is highly correlated to that of players (60). The mean YIRT1 performance of elite GFR during 'moderate' and 'high' AIC games is however similar to that reported for top level soccer referees (194).

Given that a greater HSR distance was performed during 'high' AIC games, it may be prudent to recommend that the minimum standard required to officiate AIC games be raised to promote an increase in HSR and a possible reduction in the distance of the referee from infringements. However, it is important to consider these results in context. The role of the referee in IFTS is first and foremost, to ensure that the game is played in accordance with the rules. There is currently no evidence demonstrating that a greater HSR distance completed by elite IFTS referees during competitive games equates to a greater number of correct decisions or equally fewer incorrect decisions. Further, a greater proximity to infringements does not guarantee that decisions will be correct. In soccer, elite referees made ~8% more errors during the second half of match play, with 23% of all incorrect decisions occurring during the last 15 min period of the game, despite no change in the distance from infringements (16). This does not infer that the current minimum standard required in the YIRT1 is entirely reflective of the physical fitness level needed to officiate at the elite level of Gaelic football. Rather, further research examining the interaction between the activity profile, physical fitness level and decision making ability is required to ensure the optimal physical preparation of elite GFR.

7.2 Practical applications

The current study provides researchers and practitioners with a unique set of movement category velocity thresholds specific to elite GFR. These categories are derived directly from the match activity data and provide a suitable alternative to the arbitrary categories used in the analysis of IFTS referees. The use of these categories in the analysis of activity data resulted in practically meaningful differences in the distance covered in each movement category, in particular the increased HSR and VHSR distances compared to arbitrary categories. The method used in the present study also permits the formation of both group and individual-specific movement category velocity thresholds that can be regularly and efficiently updated without the need for dedicated testing sessions or expensive laboratory equipment.

The current study provides, for the first time, a detailed analysis of the activity profile of elite GFR during both NFL and AIC games. These findings also provide the necessary information regarding the competitive level differences which exist both within and between the NFL and AIC. The improved understanding of the activity profile of elite GFR during match play will assist coaches in the design of appropriate training programmes and conditioning drills that are in line with the principles of training, namely specificity, overload and individualisation, to promote the necessary physical development of elite GFR. Considering the games analysed in the present study are of the highest standard in Gaelic football, this information will also provide referees at the sub-elite and developmental levels with an insight into the requirements of elite refereeing.

Examination of the temporal changes during match play identified the first quarter as the most intense period of match play during both the NFL and AIC, which was consistent across virtually all divisions and phases of each competition. Coaches working with elite GFR should therefore ensure that they are suitably familiar with and proficient in the performance of a warm-up routine prior to the start of match play. It is imperative that a period of time and a specific section of the playing area be provided to elite GFR prior to games in the NFL and AIC to facilitate this warm-up. The current research also demonstrates the minimal differences that exist in the activity profile of elite GFR between age groups and highlights the low number of games officiated by referees at the upper limit of the current age restrictions. A review of the efficacy of the mandatory age limit is warranted, with consideration given to referees who wish to continue officiating at national level beyond the current mandatory retirement age, provided they can maintain the required physical fitness and officiating standards.

Training of elite GFR has traditionally involved continuous running at low and moderate intensities. The findings in the present study provide clear evidence to support the design of training programmes that include conditioning drills involving both HSR ($>4.87 \text{ m}\cdot\text{s}^{-1}$) and VHSR ($>6.49 \text{ m}\cdot\text{s}^{-1}$) bouts of different distances and durations, interspersed with periods of low speed activity in conjunction with low-intensity, continuous running sessions. Training programmes should also involve running bouts that exceed the distances and speeds attained during match play to ensure optimal physical development and reduce the risk of injury.

7.3 Limitations

It is important to consider the limitations associated with the findings in the current research. Firstly, the velocity thresholds were derived from the match activity data which is a representation of the referee's movement during the game only. These thresholds were not examined against objective measures of either physical or physiological capacity. It is therefore, not possible to definitively explain the reasons for the lower velocity thresholds in the present study compared to those used previously in the analysis of elite IFTS.

Secondly, although a rigorous statistical approach was used to examine the activity profile and temporal changes of elite GFR during games in the NFL and AIC, a number of contextual factors were not controlled for which may influence the activity profile of elite GFR. These include the environmental conditions, stadium, points difference, activity of the players, and ball in play time. Examination of temporal changes involved comparison of match quarters which represented the first and last 15 min period of each half. These periods, although in line with previous studies examining the activity profile of elite IFTS, are arbitrary in duration. Examination of the activity profile during shorter epochs of 1 – 5 min using segmental and rolling analysis methods may be more sensitive to the intricacies of competitive match play and provide a greater insight into the peak activity periods. Analysis of temporal changes in the absence of positional data and information on the decision making accuracy may not be sufficient to confirm or reject the presence of fatigue during competitive match play and warrants further investigation.

Finally, the influence of age, experience, and physical fitness on the activity profile of elite GFR involved the discretisation of these continuous variables into three separate groups based on rank order. The categorisation of these continuous variables may have reduced the statistical power. This approach also resulted in different classifications for the three groups between the NFL and AIC which limits comparisons of groups between the NFL and AIC.

7.4 Future research

The current research addresses a number of gaps in the scientific literature and provides important practical information to assist in the physical preparation of GFR. However, a number of areas related to the performance of elite GFR remain unexplored. To build on the findings of the present study future research should aim to develop a more holistic understating of GFR performance. This should involve assessment of the activity profile of elite GFR and the simultaneous examination of player activity data, positioning of the referee from the ball and infringements and accuracy of decisions during competitive inter-county match play.

Future research should also compare the effectiveness of a number of training methodologies to improve the physical fitness levels of elite GFR. In particular, studies should examine if training programmes that consist primarily of low volume, HSR and VHRS bouts provide a superior training stimulus to traditional training methods involving high volume, moderate-intensity continuous running. Training programmes that are time efficient and provide the necessary training stimulus to improve fitness levels are of considerable interest to elite GFR and coaching staff given their amateur status and limited training time. Such studies would also provide a solid evidence-base to underpin the transition from traditional training methodologies to a more contemporary approach.

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APPENDICES

Appendix 1

Ollscoil Chathair Bhaile Átha Cliath
Dublin City University



Mr Aidan Brady
School of Health and Human Performance

12th April 2018

REC Reference: DCUREC/2018/041
Proposal Title: Officiating in Gaelic Games: Application of Sports Science and Technology
Applicant(s): Mr Aidan Brady, Professor Niall Moyna

Dear Aidan,

Further to expedited review, the DCU Research Ethics Committee approves this research proposal.

Materials used to recruit participants should note that ethical approval for this project has been obtained from the Dublin City University Research Ethics Committee.

Should substantial modifications to the research protocol be required at a later stage, a further amendment submission should be made to the REC.

Yours sincerely,

A handwritten signature in blue ink that reads 'Dónal O'Gorman'.

Dr Dónal O'Gorman
Chairperson
DCU Research Ethics Committee



Taighde & Nuálaíocht Tacaíocht
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DUBLIN CITY UNIVERSITY (DCU)

Plain Language Statement

Project Title:	Officiating in Gaelic Games: Application of Sports Science and Technology
Principal investigator:	Prof. Niall Moyna, School of Health and Human Performance, DCU
Other Investigator(s):	Mr. Aidan Brady, School of Health and Human Performance, DCU Dr. Andrew McCarren, School of Computing, DCU
Contact Details:	(01) 7008802, niall.moyna@dcu.ie (01) 7008470, aidan.brady39@mail.dcu.ie (01) 7008456, andrew.mccarren@dcu.ie

Introduction to the Research Study

Gaelic football and hurling referees are responsible for enforcing the laws of the game, regulating the behaviour of the players, and their decisions can influence the outcome of a game. Global positioning systems (GPS), have become a popular technology for evaluating the movement characteristics of referees in team sports such as soccer, rugby and Australian football. However, there is currently no information on the movement characteristics of Gaelic football and hurling referees. The primary purpose of this study is to measure the movement characteristics such as total distance covered, and the number of sprints performed in elite Gaelic football and hurling referees. The physiological demands that are placed on Gaelic football and hurling referees will also be assessed by continuously measuring heart rate, and finally blood lactate levels will be measured before, at half time and at the end of selected games to evaluate the metabolic demands on the muscles. Understanding the physical, physiological and metabolic demands while officiating during competitive match play will provide sports conditioning coaches with important information required to develop effective sports-specific training programs, and field-based fitness tests for Gaelic football and hurling referees.

Participation in the Research Study will involve the following

- You will wear a global positioning satellite (GPS) tracking device and heart rate monitor during all competitive games in which you are selected to officiate during the 2018, 2019 and 2020 GAA seasons.
- Before each game you will be fitted with a heart rate monitor and GPS tracking device.
- The GPS device will be placed in a pouch and worn in a custom designed harness (Figure 1).

- At selected games during the 2018, 2019 and 2020 GAA seasons, a small sample of blood will be taken from your earlobe before the game, at half time and at full time.
- You will complete the Yo-Yo intermittent recovery test prior to the start of the 2018, 2019 and 2020 seasons and prior to the start of the Championship for each year.
- You will complete 3 maximal effort 30 metre sprints prior to the start of the 2018, 2019 and 2020 seasons and prior to the start of the Championship for each year.
- You will make one visit to the Human Performance Laboratory at DCU.
- You will not take any food or beverages, except water, for 4 hours before your visit to DCU.
- You will not do any strenuous exercise for 24 hours before your visit to DCU.
- During the visit to DCU you will have your height and weight measured. You will then have your maximal aerobic capacity (VO₂ max) assessed using a treadmill test.
- During the exercise test you will wear a heart rate monitor around your chest, have a nose clip on and breath through a mouthpiece.
- The exercise test will involve running on a treadmill until you reach exhaustion.
- During this strenuous exercise test, you may feel out of breath and your legs may feel tired.
- While you will be encouraged to run for as long as you can, you are able to stop this test at any point, if you wish to do so.
- During the 2016 and 2017 All-Ireland senior Championships, as part of your involvement with the GAA national panel of referees, you wore a GPS tracking device and heart rate monitor in all competitive intercounty games in which you were selected to officiate.
- You also completed the Yo-Yo intermittent recovery test prior to these Championships with all data collected as part of the normal training and competition schedule.
- We now wish to include this data in our analysis of the physical and physiological demands of refereeing.
- We are seeking your permission to include the data from 2016 and 2017 in our analysis, something known as retrospective analysis.



Figure 1. GPS device and custom made vest

Potential risks from involvement in the Research Study

- You may experience some muscle soreness in your legs or nausea following exercise.
- Exercise carries with it a very small risk of injury, abnormal heart rhythms, heart attack or death. The likelihood of these risks in a healthy asymptomatic population is extremely low.

- This study is not investigating the risk of injury or any medical condition.
- DCU has the facilities and personnel to deal with any emergencies that arise and an emergency plan is in place. An emergency room and automated external defibrillator (AED) are available onsite.
- The research team are appropriately qualified and experienced with all testing involved.

Benefits from involvement in the Research Study

- You will be provided with a summary of your own match performance and fitness results and a lay summary of the overall test results.

Arrangements to protect confidentiality of data

- Dublin City University will protect your confidentiality with regard to your part in this study. Your information will be assigned a unique code, which will protect your identity. All information will be stored securely and saved in a password-protected file in a computer at DCU. Hardcopy files will be stored in a secure, locked filing cabinet in DCU.
- Your identity and other personal information will not be revealed or published. The study findings may be presented at scientific meetings and published in a scientific journal but your identity will not be divulged and only presented as part of a group.
- Only Prof Niall Moyna, Mr. Aidan Brady and Dr. Andrew McCarren will have access to the data.
- Confidentiality of information provided can only be protected within the limitations of the law. It is possible for data to be subject to subpoena, freedom of information claim or mandated reporting by some professions.

Advice as to whether or not data is to be destroyed after a minimum period

Electronic data will be kept indefinitely for future research. Hard copies of data collection sheets will be shredded by Prof. Moyna after 5 years in accordance with DCU policy.

Involvement in the Research Study is voluntary

Involvement in this study is completely voluntary. You may withdraw from the Research Study at any point. You are under no obligation to stay involved if you do not wish to do so. There will be no penalty for withdrawing before all stages of the Research Study have been completed.

If participants have concerns about this study and wish to contact an independent person, please contact:

The Secretary, Dublin City University Research Ethics Committee, c/o Office of the Vice-President for Research, Dublin City University, Dublin 9. Tel 01-7008000.



DUBLIN CITY UNIVERSITY (DCU)

Informed Consent Form

Project Title:	Officiating in Gaelic Games: Application of Sports Science and Technology.
Principal investigator:	Prof. Niall Moyna, School of Health and Human Performance, DCU
Other Investigator(s):	Mr. Aidan Brady, School of Health and Human Performance, DCU Dr. Andrew McCarren, School of Computing, DCU
Contact Details:	(01) 7008802, niall.moyna@dcu.ie (01) 7008470, aidan.brady39@mail.dcu.ie (01) 7008456, andrew.mccarren@dcu.ie

Purpose of the research

To measure selected movement characteristics, physiological and metabolic responses in elite Gaelic Football and Hurling referees during competitive match-play.

Participant Requirements

- I will make one visit to DCU. During my visit, I will have my height and weight measured and my maximal aerobic capacity assessed using a treadmill test.
- I will not take any food or beverages, except water, for 4 hours before I visit DCU.
- I will not do any strenuous exercise for 24 hours before I visit DCU.
- In addition, I will wear a global positioning satellite (GPS) tracking device and heart rate monitor during all competitive games in which I am selected to officiate in during the 2018, 2019 and 2020 GAA seasons.
- At selected games during the 2018, 2019 and 2020 GAA seasons, a small sample of blood will be taken from my earlobe before the game, at half time and at full time.
- I will complete the Yo-Yo intermittent recovery test prior to the start of the 2018, 2019 and 2020 seasons and prior to the start of the Championship for each year.
- I will complete 3 maximal effort 30 metre sprints prior to the start of the 2018, 2019 and 2020 seasons and prior to the start of the Championship for each year.
- During the 2016 and 2017 All-Ireland senior Championships, as part of my involvement with the GAA national panel of referees, I wore a GPS tracking device and heart rate monitor in all competitive intercounty games in which I was selected to officiate.

- I also completed the Yo-Yo intermittent recovery test on two occasions during each season with all data collected as part of the normal training and competition schedule.
- The investigators now wish to include the data from 2016 and 2017 in their analysis of the physical and physiological demands of refereeing.
- I am providing permission to use my data collected during 2016 and 2017 in the analysis.

Confirmation of particular requirements as highlighted in the Plain Language Statement

Please complete the following (Tick Yes or No for each question)

I have read the Plain Language Statement (or had it read to me) Yes No

I understand the information provided Yes No

I have had an opportunity to ask questions and discuss this study Yes No

I have received satisfactory answers to all my questions Yes No

Confirmation that involvement in the Research Study is voluntary

Involvement in this study is completely voluntary. I may withdraw from the study at any point. I am under no obligation to stay involved if I do not wish to do so. I will not receive any penalties for withdrawing before all stages of the Research Study have been completed.

Advice as to arrangements to be made to protect confidentiality of data, including that confidentiality of information provided is subject to legal limitations

Dublin City University will protect my confidentiality. My information will be assigned a unique code, which will protect my identity. All information will be stored securely and saved in a password-protected file in a computer at DCU. Hardcopy files will be stored in a secure, locked filing cabinet in DCU.

The study findings may be presented at scientific meetings and published in a scientific journal but my identity will not be divulged and only presented as part of a group. The named investigators will have access to the data. All hard copies of data collection sheets will be shredded after 5 years by Prof. Niall Moyna. Electronic data will be kept indefinitely for future research.

My confidentiality of information provided can only be protected within the limitations of the law. It is possible for data to be subject to subpoena, freedom of information claim or mandated reporting by some professions.

Signature:

I have read and understood the information in this form. My questions and concerns have been answered by the researchers, and I have a copy of this consent form. Therefore, I consent to take part in this research project.

Participants Signature: _____

Name in Block Capitals: _____

Witness: _____

Date: _____

Appendix 2

Ollscoil Chathair Bhaile Átha Cliath
Dublin City University



Prof. Niall Moyna
School of Health and Human Performance

18th January 2021

REC Reference: DCUREC/2020/275

Proposal Title: Effect of ageing and refereeing experience on physical fitness and the running performance profile of elite Gaelic football and hurling referees

Applicant(s): Prof. Niall Moyna, Mr. Aidan Brady, and Dr. Andrew McCarren

Dear Prof. Moyna,

Further to expedited review, the DCU Research Ethics Committee approves this research proposal.

Materials used to recruit participants should note that ethical approval for this project has been obtained from the Dublin City University Research Ethics Committee.

Should substantial modifications to the research protocol be required at a later stage, a further amendment submission should be made to the REC.

Yours sincerely,

A handwritten signature in cursive script that reads 'Geraldine Scanlon'.

Dr Geraldine Scanlon
Chairperson
DCU Research Ethics Committee



Taighde & Nuálaíocht Tacaíocht
Ollscoil Chathair Bhaile Átha Cliath,
Baile Átha Cliath, Éire

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DUBLIN CITY UNIVERSITY (DCU)

Plain Language Statement

- Project Title:** Effect of ageing and refereeing experience on physical fitness and the running performance profile of elite Gaelic football and hurling referees.
- Principal investigator:** Prof. Niall Moyna, School of Health and Human Performance, DCU
- Other Investigator(s):** Mr. Aidan Brady, School of Health and Human Performance, DCU
Dr. Andrew McCarren, School of Computing, DCU
- Contact Details:** (01) 7008802, niall.moyna@dcu.ie
(02) 7008470, aidan.brady39@mail.dcu.ie
(02) 7008456, andrew.mccarren@dcu.ie

Introduction to the Research Study

Gaelic football and hurling referees are responsible for enforcing the laws of the game, regulating the behaviour of the players, and their decisions can influence the outcome of a game. In order to optimally officiate referees must keep up with play at all times which requires a high level of physical fitness. At present, referees are not permitted to officiate at intercounty level once they reach an age of 50 due in part to potential age-related declines in physical fitness. No evidence is currently available to support this. The primary purpose of this study is to examine the impact of ageing on physical fitness in elite intercounty Gaelic football and hurling referees. This research will also investigate the relation between referee experience and running demands such as the total distance covered and the number of sprints, the physiological demands by continuously measuring your heart rate, and finally the metabolic demands by measuring your blood lactate levels before, at half time and at the end of selected games. Understanding the relation between age and referee experience with these demands will provide sports conditioning coaches with important information required to target any potential age-related declines through the development of sports-specific training programs.

Participation in the Research Study will involve the following

- You will wear a global positioning satellite (GPS) tracking device and heart rate monitor during all competitive games in which you are selected to officiate during the 2021 and 2022 GAA seasons.
- The GPS device will be placed in a pouch and worn in a custom designed harness (Figure 1).
- At selected games during the 2021 and 2022 GAA seasons, a small sample of blood will be taken from your earlobe before the game, at half time and at full time.
- You will complete the Yo-Yo intermittent recovery test prior to the start of the 2021 and 2022 seasons and prior to the start of the Championship for each year.
- The Yo-Yo intermittent recovery test consists of 2x20 metre shuttle runs at increasing speeds, interspersed with a 10-second recovery period (controlled by audio signals).
- Failure to complete a shuttle will result in a verbal warning. A second failure will end your attempt.
- The Yo-Yo intermittent recovery test will be approximately 13-19 minutes in duration.
- You will complete 3 maximal effort 40 metre sprints, interspersed with a 90-second recovery period, prior to the start of the 2021 and 2022 seasons and prior to the start of the Championship for each year.
- You will make one visit to the Human Performance Laboratory at DCU each year.
- You will not take any food or beverages, except water, for 4 hours before your visits to DCU.
- You will not do any strenuous exercise for 24 hours before your visits to DCU.
- During the visits to DCU you will have your height and weight measured. You will then have your maximal aerobic capacity (VO₂ max) assessed using a treadmill test.
- During the exercise test you will wear a heart rate monitor around your chest and breath through a face mask.
- The exercise test will involve running on a treadmill until you reach exhaustion.
- The exercise test will be approximately 6 – 15 minutes in duration.
- During this strenuous exercise test, you may feel out of breath and your legs may feel tired.
- While you will be encouraged to run for as long as you can, you are able to stop this test at any point, if you wish to do so.
- To assess your experience levels, you will complete a short questionnaire pertaining to the number of years you have been refereeing and at what competitive level.



Figure 1. GPS device and custom made vest

Potential risks from involvement in the Research Study

- You may experience some muscle soreness in your legs or nausea following exercise.
- Exercise carries with it a very small risk of injury, abnormal heart rhythms, heart attack or death. The likelihood of these risks in a healthy asymptomatic population is extremely low.
- This study is not investigating the risk of injury or any medical condition.
- DCU has the facilities and personnel to deal with any emergencies that arise and an emergency plan is in place. An emergency room and automated external defibrillator (AED) are available onsite.
- The research team are appropriately qualified and experienced with all testing involved.

Benefits from involvement in the Research Study

You will be provided with a summary of your own match performance and fitness results and a lay summary of the overall test results.

How will we process your personal data?

Upon entry to the study, your name and age will be recorded. You will then be provided with a unique study code which will be used on all future documentation related to you. This information is necessary to examine the impact of ageing on physical fitness and the running demands during competitive match-play. At all times, this project will be GDPR compliant with the handling and processing of personal data in line with DCU data protection policies. The data controller is Dublin City University (DCU). You have the right to access your own personal data and can do so at any time by contacting the DCU Data Protection Officer, Mr. Martin Ward (data.protection@dcu.ie, Ph: 7005118 / 7008257).

How will we protect your privacy?

All study data will be stored securely in DCU either in paper form in a secure filing cabinet, and/or saved on the Google Drive server behind the DCU secured server. The investigators, Prof. Niall Moyna, Mr. Aidan Brady and Dr. Andrew McCarren, alone will have access to the data. All study participants will be given a study code upon entering the study. Your name will appear beside this code on a paper-based master sheet that will be held in confidence by Professor Moyna. This master sheet is the only link between your name and your study code in the electronic files. Your study code number will appear on all study documentation from there onwards. There will be no way in which you may be identified in the reported study findings.

How will the data be used and subsequently disposed of?

In addition, the master sheet containing your name and your assigned code will be destroyed 2 years after data collection is complete. After this point, it will no longer be possible to identify your data, in which case it will no longer be possible for you to withdraw the data from the study. However, this now anonymous data will be stored indefinitely and used in future research and scientific publications. We hope to write the data gathered from this study for publication in a peer-reviewed scientific journal. It is also anticipated that some of the data will be used for future studies where we would seek to further explore the temporal changes in the running demands experienced by referees during competitive match-play.

What are the legal limitations to data confidentiality?

Your identity, or other personal information will not be revealed or published. However, confidentiality of information provided can only be protected within the limitations of the law. It is possible for data to be subject to subpoena, freedom of information claim or mandated reporting by some profession.

Can I change my mind at any stage and withdraw from the study?

Involvement within this research project is purely voluntary. If at any time during the study you are uncomfortable with any of the testing or protocols, or if you can no longer commit to the study for whatever reason, you have the option to withdraw from the study up until the date of the final data collection. If you are a DCU student or will be a DCU student in the future, withdrawal will not result in any penalty or affect your rights as a student of DCU, or your participation in recreational or competitive sport at DCU. Any participants who share a relationship of any kind with any of the researchers relevant to this study will not be affected in any way with regard to their studies or professional pursuits throughout the entire duration of this study.

If participants have concerns about this study and wish to contact an independent person, please contact:

The Secretary, Dublin City University Research Ethics Committee, c/o Office of the Vice-President for Research, Dublin City University, Dublin 9. Tel 01-7008000.



DUBLIN CITY UNIVERSITY (DCU)

Informed Consent Form

Project Title:	Effect of ageing and refereeing experience on physical fitness and the running performance profile of elite Gaelic football and hurling referees.
Principal investigator:	Prof. Niall Moyna, School of Health and Human Performance, DCU
Other Investigator(s):	Mr. Aidan Brady, School of Health and Human Performance, DCU Dr. Andrew McCarren, School of Computing, DCU
Contact Details:	(01) 7008802, niall.moyna@dcu.ie (02) 7008470, aidan.brady39@mail.dcu.ie (02) 7008456, andrew.mccarren@dcu.ie

Purpose of the research

To examine the impact of ageing on physical fitness and to investigate the relation between refereeing experience with selected movement characteristics, physiological and metabolic responses in elite Gaelic football and hurling referees during competitive match-play.

Participant Requirements

- I will wear a global positioning satellite (GPS) tracking device and heart rate monitor during all competitive games in which I am selected to officiate during the 2021 and 2022 GAA seasons.
- At selected games during the 2021 and 2022 GAA seasons, I will have a small sample of blood taken from my earlobe before the game, at half time and at full time.
- I will complete the Yo-Yo intermittent recovery test prior to the start of the 2021 and 2022 seasons and prior to the start of the Championship for each year.
- The Yo-Yo intermittent recovery test consists of 2x20 metre shuttle runs at increasing speeds, interspersed with a 10-second recovery period (controlled by audio signals).

- If I fail to complete a shuttle I will receive a verbal warning. A second failure will end my attempt.
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- The exercise test will involve running on a treadmill until I reach exhaustion.
- The exercise test will be approximately 6 – 15 minutes in duration.
- During this strenuous exercise test, I may feel out of breath and my legs may feel tired.
- While I will be encouraged to run for as long as I can, I am able to stop this test at any point, if I wish to do so.
- To assess my experience levels, I will complete a short questionnaire pertaining to the number of years I have been refereeing and at what competitive level.

Confirmation of particular requirements as highlighted in the Plain Language Statement

Please complete the following (Tick Yes or No for each question)

- | | | |
|---|------------------------------|-----------------------------|
| <i>I have read the Plain Language Statement (or had it read to me)</i> | Yes <input type="checkbox"/> | No <input type="checkbox"/> |
| <i>I understand the information provided</i> | Yes <input type="checkbox"/> | No <input type="checkbox"/> |
| <i>I understand the information provided in relation to data protection</i> | Yes <input type="checkbox"/> | No <input type="checkbox"/> |
| <i>I have had an opportunity to ask questions and discuss this study</i> | Yes <input type="checkbox"/> | No <input type="checkbox"/> |
| <i>I have received satisfactory answers to all my questions</i> | Yes <input type="checkbox"/> | No <input type="checkbox"/> |

Confirmation that involvement in the Research Study is voluntary

Involvement in this study is completely voluntary. I may withdraw from the study at any point. I am under no obligation to stay involved if I do not wish to do so. I will not receive any penalties for withdrawing before all stages of the Research Study have been completed.

Advice as to arrangements to be made to protect confidentiality of data, including that confidentiality of information provided is subject to legal limitations

Dublin City University will protect my confidentiality. My information will be assigned a unique code, which will protect my identity. All information will be stored securely and saved in a password-protected file in a computer at DCU. Hardcopy files will be stored in a secure, locked filing cabinet in DCU.

The study findings may be presented at scientific meetings and published in a scientific journal but my identity will not be divulged and only presented as part of a group. The named investigators will have access to the data. All hard copies of data collection sheets will be shredded after 2 years by Prof. Niall Moyna. Electronic data will be kept indefinitely for future research.

My confidentiality of information provided can only be protected within the limitations of the law. It is possible for data to be subject to subpoena, freedom of information claim or mandated reporting by some professions.

Signature:

I have read and understood the information in this form. My questions and concerns have been answered by the researchers, and I have a copy of this consent form. Therefore, I consent to take part in this research project.

Participants Signature: _____

Name in Block Capitals: _____

Witness: _____

Date: _____