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RUNNING HEAD: Sport science of Australian football

TITLE: Applied sport science of Australian football: a systematic review

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Abstract

Background In recent years, there has been a large expansion in literature pertaining to the game of Australian football (AF). Furthermore, there have been a number of rule changes that are likely to have changed the demands of the game. Based on these advances and changes, it seemed important to conduct a review assessing the scientific literature surrounding the sport.

Objective The review evaluates the match demands of AF, the qualities required for success, and the impact training and competition have on adaptation, injury, and fatigue.

Methods A systematic search of PubMed, CINAHL, SPORTDiscus, Web of Science, and Scopus for AF literature was conducted; studies investigating match demands, physical qualities, training practices, and injury were included. Weighted means and standard deviations were calculated for match demands and physical and anthropometric profiles across playing standards.

Results A total of 1830 articles were retrieved in the initial search, with 888 removed as duplicates, 626 were removed for being non-relevant and a further 152 were removed for being AF papers, but not relevant to the review. As such, 164 AF papers were included in the review. Due to the intermittent high-intensity nature of match-play, players need a wide range of physical and technical qualities to excel, with speed, aerobic fitness, reactive agility, and well-developed lean mass being central to success. Training for AF at the elite level is associated with high workloads, with players engaging in numerous training modalities; even altitude and heat training camps have been utilised by Australian Football League (AFL) teams to further augment fitness improvements. While high chronic workloads can be tolerated and are needed for improving physical qualities, careful planning and monitoring of internal and external workloads is required to minimise sharp spikes in load that are associated with injury.

Conclusions There is a complex interaction between numerous contextual factors that influence the match demands that are discussed in this review. Whilst players must have the physical capacities to cope with the intense physical demands of AF matches, the successful execution of technical skills during match-play is central to success. To develop these skills and attributes, specific and carefully planned and monitored training must be performed over a number of years.

Key Points

- Whilst effective technical involvements are central to Australian football match success physical activity profiles are linked to the number of technical involvements.
- A broad range of physical qualities are required for success in Australian football, with aerobic fitness, speed, agility, and body composition being the most important.

- High workloads develop aerobic fitness and protect against injury; sharp spikes in acute load are linked to increases in injury incidence in Australian football players.

1 Introduction

The game of Australian football (AF) is a contact team sport played on a large oval field (Figure 1). There is one professional league of AF, the Australian Football League (AFL) consisting of 18 teams. The next tier of AF is sub-elite (semi-professional) and consists of the 5 respective state leagues which, along with amateur AF, include youth and senior teams. Match-play is intermittent in nature with players performing numerous bouts of high-intensity activity (e.g. sprinting, high-speed running, and tackling) interspersed with periods of lower-intensity activity (e.g. walking and jogging) [1]. The game is made up of 2 teams of 22 players; 18 on-field and 4 interchange players, with currently up to 90 interchanges per team permitted at the elite level. The game is divided into 20 minute quarters with time added to the end of each quarter for any stoppages in play. There is a 6-minute rest at quarter and three-quarter time and a 20-minute rest period at half-time. Players are typically divided into three positional groups, forwards, midfielders, and defenders, with 6 players in each positional group (Figure 1). In some cases, players are grouped into nomadic (midfielders, small forwards, and small defenders) or fixed position players (tall forwards and tall backs). However, throughout the literature, the grouping of players into positional groups is inconsistent which makes it difficult to pool data from numerous studies. Players are required to maintain possession of the football and advance it into a scoring position by either passing (handballing) or kicking the ball to a teammate. Points can be scored by either kicking the ball through the two middle (six points), or two outer posts (one point).

FIGURE 1 NEAR HERE

Due to the size of the field (Figure 1), and average playing time (98.4 ± 11.6 min), players cover large distances at high intensities, greater than other football codes [2]. Furthermore, in the AFL, each team competes in a minimum of 22 weekly fixture rounds, with a potential 4 additional finals matches. In addition to the physical demands, players must successfully execute numerous technical actions over the course of a game, such as kicking, catching, handballing and tackling [3]. As such, they are required to have well-developed physical and technical abilities in order to be successful.

In 2010, a review of the scientific literature regarding the match demands of AF was conducted [1]. However, since this review there have been numerous advances in on-field and off-field practices, as well as rule changes, which are likely to have significantly altered the movement patterns of players and the understanding of the game. These changes have led to a growth in sport science literature since this previous review. A search of "Australian rules football" OR "Australian football" OR "Australian football league" on Scopus from its inception to the previous review in 2010 returned 325 results, whereas the same search from 2011 to 2017 returned 471 results. This proliferation in the scientific literature, along with rule changes, and advances in microtechnology, clearly warrants the need for an updated review of the literature.

With this in mind, the aim of the current review is to (1) provide an update on the match demands, (2) determine the physical qualities required for successful participation in AF, and (3) document the potential positive and negative responses to training and competition.

2 Methods

To carry out this review, a systematic search of the literature was performed in PubMed, CINAHL, SPORTDiscus, Web of Science, and Scopus for English-language peer reviewed journals from inception until 12th August 2017. The titles, abstracts and key words of articles in each database were searched using the terms highlighted in Table 1.

TABLE 1 NEAR HERE

All references were imported from the databases into a reference manager application (EndNote X7, Thomson Reuters, Philadelphia, USA) before removing all duplicated articles (Figure 2). Each study was then assessed by two authors, each reading the title, abstract, and methods when required, to determine whether they met the inclusion criteria. Any study that assessed the match demands, physical qualities, or responses to competition and training at any level of AF was included. Studies that assessed the epidemiology of musculoskeletal injury, social or psychological aspects of AF, abstracts or conference proceedings, and work in non-peer reviewed journals, were excluded.

The quality of the methods used was assessed using a previously validated scale [4]. Not all of the assessment criteria were applicable to the studies used in this review, as such, only 9 of the 27 criteria were used. No studies were omitted from the review based on assessment of these criteria. Given that a wide variety of study designs and outcome variables were reported in the literature, a meta-analysis was not performed. However, weighted means and standard deviations were calculated for match demands, body composition, and physical qualities.

3 Results

3.1 Identification of Studies

A total of 1830 articles were retrieved in the initial search, with 888 removed as duplicates, 626 were removed for being non-relevant and a further 152 were removed for being AF papers, but not relevant to the review. As such, 164 AF papers were included in the review (Figure 2).

FIGURE 2 NEAR HERE

3.2 Study Characteristics

Of the 164 papers included in the review, 49 focused on the physical match demands of competition, 23 on the technical and perceptual demands, 55 on physical qualities, 16 on training interventions, 25 on training loads, and 18 on player fatigue and recovery. Some of the studies used in the review covered multiple categories.

3.3 Match demands

In recent years, microtechnology devices have been developed for use within sport to track and monitor player movements. These devices include a global positioning system (GPS) chip, which provides the position of the unit, with speed being calculated via the Doppler shift method [5]. In addition, some units include a tri-axial accelerometer and a magnetometer and gyroscope to provide information on non-running activities such as jumping and tackling. The specifications of these devices vary between manufacturers, and have developed rapidly since their inception, readers must interpret data with caution when interpreting some variables [6]. Total distance can be assessed with high levels of validity and reliability [7]. However, when measuring sprints over short distances (e.g. 10 m), GPS devices have shown poor reliability with coefficients of variation (CV) exceeding 30% for 1 and 5 Hz units, and 10.9% for 10 Hz units [6, 8]. In summary, as the sampling frequency of the GPS chip increases, the validity and reliability are improved [9]; the accuracy of devices is reduced when assessing movements over short distances when moving at high speeds or decelerating rapidly, particularly in 1 and 5 Hz devices [9].

3.3.1 Distance

The total distances covered during games ranges from 11000-13500 m at an intensity of 129 ± 13 $m{\cdot}min^{-1}$, range: 110-130 $m{\cdot}min^{-1}$ (Table 2), which is significantly greater than the other football codes [2, 10-14]. Total distance covered is dependent on several factors, with playing position [11, 13] and playing standard [11, 14] central to these differences. In comparison to other positional groups, the nomadic players (small forwards, small backs, and midfielders) cover the greatest absolute and relative distances. Specifically, midfielders and key position players have the highest and lowest work-rates, respectively [11, 13]. This is unsurprising, given the large area of the field nomadic players are required to cover in comparison to the relatively fixed positional demands of key position players.

When assessing the impact of playing standard on distances covered, the differences are less clear, with studies reporting lower [11] and higher [15] distances covered for elite players, or no difference between standards [14]. These results could be partially explained by the longer on-field time of players at the sub-elite level [11], as well as little difference in fitness qualities between players competing at the two playing levels [15]. When adult competition is compared to youth matches however, under (U) 18 players cover significantly less distance due to shorter playing times (77-81 min *vs.* 94-103 min) [16]. Furthermore, when expressed relative to playing time, elite players are shown to exert a greater work rate, covering more m per minute (129 ± 13 $m \cdot min^{-1}$) in comparison to sub-elite senior (123 ± 13 $m \cdot min^{-1}$) [11, 14] and elite youth competitions (118 ± 19 $m \cdot min^{-1}$) [16]. At amateur levels, there is a large difference between senior (103 ± 16 $m \cdot min^{-1}$) and youth players (88 ± 24 $m \cdot min^{-1}$) [17]. The differences between elite and sub-elite may be partially explained by reduced playing time at the elite level through increased rotations [11], resulting in increased rest, allowing players to maintain greater running intensities [18]. The superior physical capacities of adult players compared with youth players [19, 20] and the vast differences between elite and amateur playing standards [17] are likely to explain the differences in match demands in these groups [21]. As such, at the sub-elite level, coaches should be encouraged to regularly rotate players to increase the speed of the game so that it more closely reflects the demands of AFL competition [22]. The large gap between elite U18 competition and AFL match-play makes preparing U18 players for elite competition more complex [16]. Players drafted into the AFL need to be gradually progressed from U18 to elite adult workloads in order to minimise injury risk [23]. Given that sub-elite competition has the same match duration as AFL and a greater intensity than elite youth competition, state league competitions may act as an appropriate ‘stepping-stone’ for elite youth players progressing into the AFL.

TABLE 2 NEAR HERE

Although the playing intensities of elite AF match-play have been well documented, the majority of studies have only reported match averages, which are likely to underestimate the worst-case demands of competition. Dividing the game into three minute periods highlights there are passages of play with significantly greater playing intensities than the match average [30]. Further to this, one study assessed rolling periods ranging from 1-10 minutes [31]. The investigators reported during the peak one-minute period of match-play, players covered 199-223 $m \cdot min^{-1}$ depending on playing position, with the mobile (small) forwards covering the greatest distance [31]. Firstly, this study highlights that peak periods of competition are greater than the average demands by almost 50%, which can provide coaches with a worst-case scenario around which they can implement match specific training drills. Secondly, the mobile forwards had the highest peak period. Given the role of mobile forwards within the game, this would suggest that these peak periods are occurring at critical points, where players may have to perform key technical skills (i.e. perform continuous leads for the football, creating space for the tall forwards or completing defensive pressure acts such as tackling) alongside these elevated physical demands. However, this warrants further investigation, where the peak activity profiles during competition are assessed for both technical and physical outputs.

3.3.2 High-speed distance

Most time is spent at low-speeds in AF matches (86.6 ± 2.8%), although players are required to perform numerous high-speed running actions over the course of a game [14]. Players cover between 1300-4300 m, at an intensity of 27 ± 11 m·min^{-1} and 29 ± 7 m·min^{-1} at the elite and sub-elite levels respectively (Table 2), with approximately 2 high-speed (>3.9 m·s^{-1}) running efforts per minute [25]. Similar to total distance, the nomadic positions (e.g. mobile forwards, backs, and midfielders) cover the greatest absolute and relative (38 ± 7 m·min^{-1}) high-speed running distances [13, 18]. Elite players perform more high-speed running per minute of match-play compared with their sub-elite counterparts [11, 14, 15]. Once again, when the peak one-minute periods of the game are taken into account, players cover between 70-110 m·min^{-1} of high-speed running (>5.5 m.s^{-1}) depending on playing position, with mobile forwards covering the greatest relative distance [31]. It would seem important that players are exposed to these intensities during training so they are prepared for the worst-case demands of competition.

3.3.3 Sprinting

At the elite level, players have been reported to perform 22 ± 9 sprints (≥7 m.s^{-1}) over the course of a match, culminating in 328 ± 128 m [2]. Furthermore, players are performing 45% of these sprints with less than 30 seconds recovery [2], suggesting they often occur during periods of elevated match intensity. Although this only translates to around 1 sprint every 3 minutes, players are performing almost four times as many high-intensity accelerations in addition to these sprints [2] which are associated with a high metabolic and neuromuscular load [32]. As highlighted previously [11, 13], whilst the greatest running loads are seen in midfielders, fixed defenders perform a comparable number of high-intensity accelerations and decelerations (>2.78 m·s^{-2}; CV = 18.1%) to midfielders, higher than other positional groups [33]. This is most likely explained by the congested areas of the field that they play in, where short purposeful movements are required to either evade or mark their opponent. This could impact on the fatigue response and subsequent training following competition. The sprinting and acceleration demands are also greater at the elite level when compared to sub-elite [15] and youth [16] competition. Training acceleration qualities is likely to be more important than maximum velocity, more so for nomadic and fixed defenders.

3.3.4 Contact demands

Each player is involved in approximately 8 tackles per game, 3.9 ± 2.3 in defence and 4.0 ± 1.9 in attack [34], although numerous off-the-ball contacts are likely to significantly increase these loads. Following the validation of the contact detection algorithm in rugby league [35, 36], the same algorithm was applied to AF with less favourable results [37]. Compared to video coded contact events, the microtechnology units successfully detected 78%, showing acceptable sensitivity, although lower than rugby league (98%) [36]. Whilst the sensitivity may appear acceptable, the specificity of these units remains questionable. Over the four matches, 1510 “tackles” were detected, with only 18% verified as tackles [37]. As such, quantifying tackle loads in AF is still an issue, particularly during training. Although the contact demands of training and competition are lower than other contact sports, given the physical cost of collisions, recording these events is still important.

3.3.5 Technical demands

Like all team sports, AF players are required to perform numerous technical skills; such as tackling, disposals (handballing and kicking), and catching during a game (Table 3), with successful kicks and goal conversion rates being the most important for performance [38]. In the period between 2001 and 2015, there were various rule changes and a modernisation in approaches to player preparation [39]. This led to league-wide changes in the technical profile of matches over this period, with large increases in kicks, handballs, disposals, contested disposals and tackles over the 2005-2009 period before largely stabilising in the 2010-2015 period [39]. The reason for this initial shift (2005-2009) may have been teams adopting tactics centred on maintaining possession of the ball. Conversely, since 2010, teams have adopted a repossession style [25], where zonal defensive structures are utilised to minimise the amount of uncontested possessions players are afforded to disrupt sustained periods of possession [39]. In addition, the increase in clangers (Table 3), tackles and contested possessions may also be a result of increased physical qualities [40, 41] and match intensities over this period [16]. Elite players and elite youth players have an average 0.33-0.42 skill involvements (any touches of the football) per minute with no difference between playing standards [16]. Nomadic players have more skill involvements per minute of play compared to key position players [42], explained by their roles in both attack and defence. Players must execute these skills effectively in order to be successful [38, 43, 44] with more involvements during winning quarters; a reduction in skill efficiency results in more closely contested match quarters [3]. Furthermore, skill involvements appear to be more important at influencing coaches' perceptions of performance than physical work rates [44]. At both senior and youth levels, deliveries into the attacking 50 m zone ('inside 50') are important [38, 45, 46]. Youth players who have more contested possessions and 'inside 50s' are more likely to be selected as earlier draft picks into the AFL, suggesting these actions are vital to success [45, 46]. Moreover, the effectiveness of these actions appears more important than the total number [29]. The execution of effective skills is vital to the outcome of a game and career success, more so than the physical requirements of the sport.

TABLE 3 NEAR HERE

Although skill involvements and efficiency appear most important at determining overall match performance [38, 44], physical work-rates and technical match performance are related. Increases in high-speed running [21, 42, 47], and exertion index (sum of a weighted instantaneous, 10s and 60s speed [48]) result in more technical involvements and in some [21], but not all instances [44], increased coaches' perceptions of performance. Another study reported small relationships with GPS variables and technical and coaches perceptions of match performance [49]. Clearly the relationship between physical activities and technical actions is multi-factorial, and is likely dependent on position playing style, coaching style and team tactics [49].

3.3.6 Perceptual Demands

In addition to executing technical skills across a game, due to the open, stochastic nature of AF match-play, with both temporal and spatial uncertainty, players must make appropriate decisions by possessing relevant perceptual skills. Previous evidence indicates that decision making can be reliably assessed during match-play [50]. At a junior level, 'talent identified' U18 players had superior response accuracy to a video-based decision-making task compared to non-identified U18 players [51]. Moreover, senior elite players have better overall response accuracy on a video-based decision-making task [51, 52], but when viewing 'speeded' video clips (1-2 times), elite players actually show improvements in decision accuracy compared to the reductions seen in the sub-elite players [52]. As such, a player's ability to make accurate decisions in response to the rapidly changing scenarios that occur during match-play is vital and clearly distinguishes between playing rank.

The best methods to develop decision-making skills are still not clear. Studies have utilised video based decision-making scenarios where players watch game scenarios and highlight the best pass option [50, 52-54]. Following video-based training over 5 weeks, players have shown improvements in response accuracy, and the number of cues they fix their eyes on [54], although the transfer to on-field performance has not been shown [50]. It may be that computer-based training is too far removed from the perspective players face when making decisions on the field. This highlights that whilst computer-based training may offer some benefits to expose players to game specific scenarios, matches and game-based training are likely to be the most effective methods at improving the decision-making components of performance. Indeed, improvements in the perceptual skills across the season during competition support the notion that as players are exposed to more competitive matches, decision-making improves [50]. This evidence further highlights the need for specific training where players are faced with match specific scenarios on a regular basis [55]. Having said this, video-based training may complement on-field training, and as virtual relating technology and other types of immersive video develop there may be greater transfer due to the point of view perspective players can be exposed to.

3.4 Factors influencing match demands

3.4.1 Player Quality and Experience

Experienced players are more likely to be selected in matches than inexperienced players at the elite level [56], and increased experience has a small, positive effect on match performance [57] and match outcome [58]. High calibre players are older [25] and spend more time on-field (7.2%) compared to their low-calibre counterparts, which translates to an increase in total distance covered (9.6%) [43]. These high-quality players have also been found to be more efficient on-field than other players, performing fewer high-intensity efforts, and covering less overall distance per minute of play [25, 59]. However, compared to one of these previous studies [25], a more recent paper focusing on nomadic players, in a more successful side, showed greater playing intensity, and high-speed distance in the high calibre players [43]. High calibre players also have a greater number of involvements with the ball and more involvements relative to distance covered [43, 59]. This information implies that high quality players rely more heavily on their ability to ‘read-the-play’ and position themselves in appropriate positions to receive the ball, whereas lower quality players may have poorer perceptual skills, meaning they need to work harder physically to position themselves to become involved in play. Other studies have shown decreased running intensities [42] and increased technical involvements [57] as players become more experienced. This may result in experienced players being better able to maintain match involvements after peak periods of match-play and elevate their running outputs at critical points of a game, such as at the end of each half [30], due to less cumulated fatigue [12]. With this in mind, it is vital that first, less experienced players have substantial training time dedicated to improving the physical qualities required for AFL competition, which may take three or more seasons [19]. Secondly, these players may benefit from game-based training to expose them to match-specific scenarios, to develop their ability to make appropriate decisions and execute skills under match-related pressure and fatigue [55]. Whilst game-based training has been shown to be effective in soccer and rugby league for developing physical and technical abilities [60], further research is required to highlight the efficacy of this training approach in AF.

3.4.2 Physical Qualities

Physical qualities also influence both physical and technical match activities at the elite [18, 21, 24, 47, 57, 61], sub-elite [17, 62, 63], youth levels [64, 65], and female football [66, 67]. Overall match performance, determined from in-game technical statistics [57], disposals per minute [21] and total involvements per minute [62-64] are all increased with well-developed aerobic capacity or high-intensity running ability. One study however, showed a negative relationship between 2-km time trial performance and relative player rating [47]. This result may have been due to the playing style of the team; the aerobic, continuous nature of the 2-km test compared to the high-intensity intermittent nature of competition. Early maturing players, with increased physical qualities, cover more distance, and more high-speed distance than later maturing players during U15 matches [65]. This may have important ramifications for selection in teams at this age level and later years with a relative age effect apparent in AFL draftees [68]. Despite this, mature age AFL draftees ($\geq$ 20 years of age) actually display a reverse relative age effect, highlighting the need for continued participation in youth players, despite potential de-selection from representative teams during junior age-grades [68]. Upper-body muscular strength in nomadic players, is strongly associated with a number of in-game statistics, explaining 48% of the variance in Champion Data ranking [61]. Moreover, high-intensity running ability, aerobic fitness, and muscular strength and power are associated with increased relative distance and relative high-speed distance during matches [17, 18, 21, 61]. When peak running speed is combined with coaches’ rating of skill it is the strongest predictor of disposals and effective disposals in youth players [69].

Technical abilities are clearly pivotal to AF success [3, 44], and the relationship between physical qualities and technical performance is complex. High fitness levels minimise reductions in physical and technical performance under fatigue [24, 70, 71], in addition to reducing post-game markers of muscle damage [72]. Therefore, developing running fitness, strength, and power will help maximise overall performance in AF players. It also seems important to develop a player's game awareness and ability to 'read-the-play'. This may result in players being less reliant on physical qualities throughout the game, thus preserving energy to complete game tasks effectively and elevate work-rates at pivotal points, and when required [12, 30, 31].

3.4.3 Pacing

Pacing is the efficient use of energy across an event so that all available resources are used without compromising performance prior to the end of the event [73]. Across a game, players appear to reduce *'non-essential'* activities (e.g. walking) so they can preserve energy to perform *'essential'* activities (e.g. high-speed running and sprinting) [12, 47, 74]. This pacing strategy appears even more evident in hot conditions (>27°C), where players are mindful of minimising increases in core temperature [74, 75]. Despite these evident pacing strategies, fatigue is still apparent towards the end of a match, with most [12, 13, 24, 47, 74, 76, 77], but not all [10] studies reporting reductions in playing intensity (both total and high-speed m per minute) across match quarters, indicative of a positive pacing strategy [76]. However, when the final quarter is won, players perform more overall distance [76] or high-speed running [77]. This may be due to an increase in pressure to perform in the limited time remaining, therefore resulting in players increasing work-rates in an attempt to win the game.

The onset of fatigue appears closely linked to physical qualities [24, 47, 66] and the amount of work performed, with increased (shorter) rotations [11, 24, 47] and less first half work being associated with the maintenance of second half playing intensity [12]. Indeed, in women's football, the players with lower workloads (half-backs and half-forwards) are able to maintain running intensities over a game, whereas midfielders, who have the highest work rates and total loads, show reductions as the game progresses [76]. Similarly, after elite male players have been on-field for 5 minutes, rotated players' running intensity decreases by approximately 3% every 2 minutes [22]. Despite well-developed physical fitness, players still present reductions in work-rates as games progress [24, 66]. With this in mind, increasing player fitness and shorter rotation bouts are likely to delay the onset of fatigue, particularly for midfielders [66]. Despite this, the removal of the substitute (2015), and reductions in the number of rotations in recent years, limit the flexibility of interchange duration. Prior to 2014, teams were permitted unlimited interchanges, in 2014 and 2015, this was capped at 120, and from 2016 onwards interchanges were further reduced to 90 per team. The impact this has had on the game is unclear and further research is warranted to determine whether any changes in the match demands of AF have occurred.

3.4.4 Match Outcome and Score-line

When a game is won, there is an increase in relative distance [18, 76], but reductions in high-speed running [18], however this trend varies across a game and between positions [76]. Other studies have also shown less high-speed running during quarters won [3], which may be indicative of the team having more possession and performing fewer high-speed movements in an attempt to regain the ball [77]. However, winning teams perform more high-speed running when not in possession of the ball, and during closely contested quarters, match demands are increased with reductions in skill efficiency [3]. This pattern may reflect more even possession and more contested possessions between closely matched teams, with players having to increase work-rate off the ball to gain an advantage. This theory is supported by the increased relative distance completed by teams against stronger opposition [18, 76]. Additionally, these increased match demands are likely to cause more fatigue, which could also explain the reduction in technical performance [3, 70, 71]. Although high-speed running does not appear pivotal to game success, players must have the capacity to increase physical activities when required. Further research should look to assess the activities preceding successful and unsuccessful skill actions in order to develop game-specific training drills and determine whether there is a link between player fatigue and key match events.

3.4.5 Match Importance

Finals matches are played at an elevated intensity with an increase in total distance (11%), high-speed running (9.2%) and maximal accelerations (96.6%) [78], which may be due to competing against stronger opposition [18, 76]. This may be due to an increase in opposition quality and a potential pacing strategy employed by players over the course of the season, perhaps in an attempt to save energy or prevent injuries so they can deliver successful performances during the final stages of the season knowing that increasing their playing intensity may be important for match outcome. This theory is supported by recent evidence showing lower match intensities earlier in the season [18]. Furthermore, given the importance of finals games and the end-point of the season nearing, players appear to employ an all-out pacing strategy across these games.

3.5 Physical qualities

Given the long duration, intermittent, and contact demands of AF match-play, a broad range of physical qualities are required in order to be a successful player [20, 26, 56, 79-81] (Table 4). There is a myriad of variables that influence player success, with technical, tactical, and personality traits playing an important role [26, 80]. The difficulty in assessing technical qualities has often meant they have been overlooked in the literature and in practice, but given the activity profiles of successful teams [3, 44] and the skill qualities of ‘talented’ players they are clearly vital to success [80]. Furthermore, models assessing the ability to predict selection into a state level youth squad were more powerful for technical (89.4%) and perceptual-cognitive (89.0%) qualities, compared with physical qualities alone (84.0%) [79, 82, 83]. When both physical and technical qualities were assessed together, the greatest sensitivity for the model was achieved, predicting 95.4% of players selected [80], clearly showing physical attributes are important. Indeed, physical qualities have received great attention, and do play a role in youth player success [79-81], draft selection [84], and career progression in the AFL [26]. Over recent years, there has been a greater level of physical preparation of players entering the draft [40, 41], which may increase their preparedness to transition to full-time training in a professional environment. Despite this, it may still take 3 or more seasons of full-time training for drafted players to fully develop the physical qualities required for AFL competition [19]. As such, practitioners devote a large amount of time to develop the physical qualities of newly drafted players in order to prepare them for senior elite competition. It would be worth tracking players over the early part of their career to see how physical and technical capabilities change and how this influences career success.

3.5.1 Aerobic fitness

The importance of aerobic fitness is well-documented within the AF literature (Table 4), with players showing well-developed aerobic capacities [41]. The duration and distances covered during the game demonstrate that the ability to produce energy aerobically during match-play is vital. Other than ruckmen having lower aerobic capacities, there is little positional difference in aerobic fitness [41]. There are increases in measures of aerobic fitness as playing level increases [79, 81, 85], between drafted and non-drafted players [20, 84], and between selected and non-selected elite players [56]. In youth (U18) players however, the multi-stage fitness test was a poor predictor of selection to a state-based team compared with lower-body power and handballing accuracy [80]. However, this finding may be explained by the low multi-stage fitness test scores (12.02-12.08) as one study showed aerobic fitness only influenced draft likelihood when a multi-stage fitness test score greater than 14.01 (2660 m) was achieved [84]. At the elite level, the positive influence measures of aerobic fitness, and high-intensity running ability have on activity profiles, performance during match-play, and career success are clear [21, 24, 26, 72]. Poor aerobic fitness is also associated with an increased risk of lower limb injuries in youth (RR [relative risk] = 0.752) [86], and senior players (OR [odds ratio] = 0.994) [87]. There is also greater maintenance of kicking speed under fatigue with higher Yo-Yo Intermittent Recovery Test (IRT; Level 2) score [71]. Clearly, aerobic fitness is vital for success and should form a major focus of physical preparation.

TABLE 4 NEAR HERE

There are numerous assessments that can be carried out to determine aerobic fitness or maximal aerobic speed (MAS). Fixed distance time trials over distances of 1200-3200 m are popular within the field due to the lack of specialised equipment required, they are time efficient, and can be used to prescribe interval-based training sessions [104, 105]. Bellenger and colleagues

[104] reported that the most accurate time trial distance for estimating MAS in semi-professional AF players was 2000m, showing a 0% bias when compared to MAS derived from the University of Montreal Track Test. Time trials shorter (1500 m) and longer (3200 m) than 2000 m may over- and underestimate MAS, respectively [104, 105]. Using either 1500 or 3200 m time trial times, regression equations from elite AFL players are available to estimate MAS from a graded test on a treadmill [105]. Alternatively, the time taken to complete time trials can then be converted into average velocity to determine MAS, from which interval training can be prescribed [106]. Practitioners should therefore be mindful of the method used to assess MAS, with tests to exhaustion (e.g. 30-15 Intermittent Fitness Test), likely to produce faster final running speeds than the average velocity from a set distance time trial.

There may be periods in the season when it is not feasible to test players using maximal tests to exhaustion or when more regular monitoring is desired to assess players' responses to training. As such, submaximal running tests can be used where exercise or recovery heart rate is used to determine performance rather than distance covered or time taken to complete a set distance [99]. One study in AFL players assessed heart rate responses during and after the first 4 minutes of the Yo-Yo IRT (Level 2) and compared this to distance covered during the maximal Yo-Yo IRT. They found that heart-rate (HR) during the submaximal Yo-Yo IRT offered acceptable reliability (CV = 1.3-2.0%) and validity (r = -0.58 to -0.61), with HR at 4 min offering the most reliable measure of performance [99].

3.5.2 Speed and acceleration

Players selected for the first game of the AFL season show faster sprint times than non-selected players [56, 90]. Although one variable cannot predict career success, speed and acceleration appears to be one of the most important physical performance variables [26, 84, 107] showing clear differences between playing standards (Table 4). Better draft sprint performance over 5, 10 and 20 m are associated with being drafted and playing more AFL games over a 5-year period [20, 26]. Specifically, players with a 20 m sprint time of less than 2.99 seconds were more likely to be drafted into the AFL [84]. Repeated-sprint performance, which is heavily influenced by maximum speed [90, 92, 108, 109], is also important, distinguishing between selected and non-selected players [90], elite and sub-elite players and influencing career success [81, 91]. In addition, depending on the work-to-rest ratio and distance of the repeated-sprints, aerobic capacity also positively influences performance, but to a lesser extent than short sprint qualities [92, 108, 109]. Lower-body strength, as measured by a front squat (r = -0.60), lower-body power from a hang clean (r = -0.58), countermovement jump (r = -0.62), two-bounds for distance [96], and sum of 7 skinfolds (r = 0.61) are significantly related to maximum speed over 10 and 20 m in sub-elite and elite players [90, 101]. This suggests that improving strength and power through resistance training and minimising non-functional fat-mass could transfer to greater sprinting performance, which in turn could also improve repeated-sprint performance.

Normal sprint training and resisted sprint training over an 8-week period, with sprint volumes between 425-680 m per week over two sessions, are effective at enhancing the acceleration phase of sprinting (6-8%) and jumping performance in AF players [110]. Repeated-sprints (10 m) performed over a 4-week block, with total sprinting volumes as low as 800 m (200 m per week), improved repeated-sprint performance (5.1%) and maximal sprint speed (5.2%) in sub-elite AF players [109].

3.5.3 Agility

In AF, players must anticipate game events and evade defenders in attack, as well as respond to an opponent's movement and attempt to reduce their decision-making time in defence. Agility is a combination of physical (change-of-direction speed) and perceptual (anticipation, decision making) qualities that players are required to possess to make fast, accurate decisions and move their body appropriately [111]. Although, valid and reliable assessments of reactive agility are available [112-114], practitioners have often overlooked these assessments. Simpler, pre-planned change-of-direction speed tests are typically opted for, such as during the AFL draft [20]. Whilst smaller midfield players tend to demonstrate the best performances on the pre-planned AFL agility test utilised in the draft [41], there is little difference between playing standards [79, 84, 115], questioning the validity of the test. When players are required to change direction in response to a stimulus however, there is a difference between performers when reacting to light signals, and sport-specific cues in particular [112]. One study even showed that high calibre players were actually slower than low calibre players on a pre-planned test (1.9%; effect size [ES] = 0.35), but when reaction to movement of the assessor was required, movement time was faster in the high calibre players (5.2%; ES = 1.13) [115]. This slower change-of-direction speed may be due to less relative power (57.22 ± 7.40 $W{\cdot}kg^{-1}$ *vs.* 53.13 ± 5.91 $W{\cdot}kg^{-1}$), reactive strength (183.3 ± 34.8 $cm{\cdot}s^{-1}$ *vs.* 168.8 ± 28.6 $cm{\cdot}s^{-1}$) or 10 m sprint speed (1.91 ± 0.05 s *vs.* 1.94 ± 0.05 s) in the fast agility group [116]. Higher performing players are also less susceptible to feints than lower performers, potentially due to greater anticipation and ability to recognise movement patterns [117]. Taken together, the physical component of agility (movement speed) has lesser discriminative ability than the cognitive aspects of agility performance. [114].

In order to develop agility, we first must understand the underlying physical qualities that determine performance. Due to the complex nature of agility performance, there is a small contribution of numerous physical factors such as 10 m sprint speed, horizontal, lateral, and vertical jumping as well as lower-body strength and power [101, 111, 116, 118]. Whilst these physical factors influence movement time, they do not impact on the cognitive component of agility. Skill-based factors, such as anticipation, pattern recognition, and decision-making, play a greater role in overall agility performance [111, 114, 116]. As such, alongside developing lower-body strength and power qualities, exposing players to agility drills in training where they are required to make decisions based on the movement of an opponent and/or the position of the ball with spatial and temporal uncertainty. One study has shown improvements in agility performance in elite youth players with as little as eleven 15-minute sessions over 7 weeks. Sessions involved either 4 change-of-direction drills (pre-planned movements) or short duration, small-sided games (35-40s and 1:1 work-to-rest ratio) [119]. There was no improvement in reactive agility performance in the change-of-direction group, but moderate improvements in total agility time (3.8%) and very large improvements in decision time (31.4%) in the small-sided game group. In order to increase the number of agility manoeuvres per small sided game, coaches can (1) reduce the area per player (2) reduce the number of players or (3) use normal tackles as opposed to 2 handed touch [120]. In a relatively short space of time, agility performance can be improved, largely through improvements in perceptual skills, when sport-specific cues are used.

3.5.4 Strength and power

There is relatively little information on the muscular strength profiles of players [19], whilst there is a large amount of detail on muscular power. Ruckmen and tall position players appear to produce the greatest lower body power out of all playing positions, highlighted by greater vertical jump height in elite youth players [41]. Elite youth and senior players are more powerful in the lower-body during both stretch-shortening cycle and concentric only jumps [19, 79-81, 89]. Caia et al., [89] showed that there was little difference in lower-body strength between elite and sub-elite players, whereas countermovement jump peak power at body weight, 30% and 40% of back squat 1 repetition maximum (RM) was significantly greater in elite players. High calibre elite players also demonstrate greater lower-body power compared with low calibre players (14.4%) as well as increased lower limb stiffness [56, 95]. With this in mind, training should aim to develop whole body strength and power, particularly in recently drafted players who show lower levels of relative strength and power compared with their more experienced counterparts [19]. Strength, the ability to produce force, is a vital foundation to produce high power outputs [103, 121]. Therefore, training should focus on developing muscular power, with high force and high velocity movements and the ability to use the stretch-shortening cycle to maximise performance [122, 123]. There is relatively little information regarding the amount of resistance training required to induce changes in elite AF players. Positive changes in fat and lean mass have been shown over the pre-season period with 2-4 strength sessions per week [124]. Another study used 3 sessions per week, progressing from hypertrophy, general strength, maximum strength and power across the pre-season phase, with a reduction to 2 sessions per week in the competition phase [125]. Given appropriate training, elite players can still make moderate (ES ≥0.60) gains in lower-body power as they progress through their careers [125]. It is worth noting that players with a younger training age responded less favourably to in-season concurrent training compared to older players, with significant reductions (-4%) in upper-body power [97]. This may be due to younger players being unable to cope with higher training loads and the associated fatigue, which negatively impacts power production. Practitioners should be mindful of this when prescribing and monitoring workloads and responses to training, particularly in younger players.

3.5.5 Body composition and anthropometry

Standing height (Table 4) appears one of the most important factors in youth players [79] and in draft selection, with drafted players being taller [84]. However, stature has little influence on career success beyond the draft [26], where intra-position comparison shows little difference between players although tall defenders, tall forwards, and ruckmen are taller than the other players [41]. This is not surprising given the roles of the tall positions and ruckmen, typically being involved in contested marks for the football. Whilst body fat percentage is fairly similar between playing standards (7.8-8.5%), elite players have significantly greater fat-free, soft tissue mass than sub-elite players [19, 90, 93], and winning teams are heavier in the AFL [58]. Elite players exhibit increases in lean mass and bone mineral content as they become more experienced, most likely due to chronic exposure to regular resistance training [93, 124]. There are reductions in fat mass and increases in lean mass over the pre-season period (2-4 sessions per week), with these changes being typically maintained over much of the season. Some players may exhibit increases in fat mass towards the end of the season, potentially due to reductions in training loads (1-2 strength sessions per week) in an attempt to manage cumulative fatigue and changes in macronutrient quality and quantity [124, 126]. Body composition should be monitored across the season so that any increases in fat mass that may occur can be addressed.

Kicking performance is positively correlated with leg lean mass ($r = 0.631$) accurate kickers have 8-16% more lean mass and less body fat [98, 127, 128]. Accurate kickers also display less lower-body muscle asymmetry [127]. It is important to note however, that asymmetry is common due to chronic exposure to routine kicking actions, and increases with training exposure [129, 130]. Low body mass is a risk factor for increased injury incidence (OR = 0.887), which may be due to lighter players being unable to cope with the contact demands [87]. Taken together, practitioners should look to increase lean muscle mass in particular, whilst minimising increases in fat-mass in newly drafted players. Unilateral lower-body exercises should be incorporated into resistance training programmes to address potential left and right imbalances in fat-free mass between kicking and supporting legs.

Overall, physical qualities are important for success in AF. With regards to the player draft, aerobic fitness and 20 m sprint performance appear the most important factors associated with being drafted into the AFL [20, 26, 79, 84]. Players with a 20-m sprint less than 2.99 s and/or a multistage fitness test greater than 14.01 (2660 m) were more likely to be drafted into the AFL [84]. It is important to note though, that to develop into a successful AFL player, newly drafted players must continue to develop these qualities across their careers [125]. Assessing and training change-of-direction speed with no perceptual

-cognitive component is unlikely to be useful in distinguishing player rank or developing sport-specific agility. Players must be exposed to a range of scenarios where they are required to make fast decisions and movements in response to match-specific situations. Clearly players need to have a broad range of physical qualities to be successful in AF.

3.6 Training Load

The competitive season runs from March until October with the pre-season starting in November, lasting 12-22 weeks [131, 132]. During pre-season, there is more time devoted to conditioning compared to the in-season phase, as well as higher overall training loads [132-134]. Due to the timing of pre-season, there is a Christmas break after 4-6 weeks of training, lasting 10-14 days [135]. During this break, players are largely able to maintain training adaptations, although small increases in skinfold thickness [135] and 2km time trial time [131] have been observed. These changes in performance over the break are dependent on a number of factors. Coaches have been seen to overreach players in the weeks leading to the break, so that the Christmas period can be used as a recovery mesocycle. A study in elite AF players had training loads of almost 8000 high-speed running m ($>4.7 m.s^{-1}$), and a rating of perceived exertion (RPE) load of approximately 7000 arbitrary units, (AU) equating to almost 17 hours of very hard training (category ratio; CR-10 RPE = 7) the week prior to the Christmas break [135]. On the other hand, a study of senior, state-level players had RPE loads of only 2000 AU, equating to 5 hours of very hard training. Whilst players in both studies were given unsupervised programmes to conduct during the break, the higher training loads in elite players prior to the break may have been the reason for the maintenance of aerobic fitness [135], compared to the slight reduction seen in sub-elite players [131]. Although high workloads may be beneficial for maintaining adaptations over the Christmas break, these loads must be reached in a controlled, and if possible, systematic fashion.

As players are unlikely to return to pre-injury form following substantial lay-offs (i.e. post-anterior cruciate ligament [ACL] injury) [136], numerous studies have assessed the relationship between training load and injury in AF players in an attempt to understand risk factors for injury. High training loads do not appear to be the issue, they actually protect against injury, with low chronic workloads (<1000 AU, or <5000 m per week) associated with greater injury risk [23, 131, 137-141]. Furthermore, players who complete a greater proportion of pre-season and have higher loads during this period have fewer injuries [139] and are available for more in-season training sessions and games [137]. Rather, injury risk is largely dependent on the load that players have been prepared for, with sharp spikes in workload the biggest risk factor for injuries, which can be assessed by calculating the acute:chronic workload ratio (ACWR) [23, 140-145].

An acute load ~80-120% of the chronic load was shown as the optimum zone for minimising injury risk [140, 142]; players with higher chronic loads can cope with greater ACWR values [140]. It is not possible however, to be in this zone constantly, otherwise no overload or recovery would occur, two basic principles of training periodisation [146]. Variation in the training dose between microcycles is important for reducing injury risk; high training loads cannot be applied over a number of weeks [131, 133, 144]. Therefore, practitioners need to manage changes in training load appropriately between and within microcycles. When acute load is two times or more than chronic load (i.e. a sharp spike in load; ACWR > 2.0); there is up to an 8-fold increase in injury risk in the current and subsequent weeks during both in-season and pre-season phases [23]. The initial work conducted on the ACWR in AF utilised the acute window as the previous 7 days of training and the chronic window as the average of the previous 28 days of training [23]. One issue with this method is the need to have a 28-day period of training before a true ACWR can be established and injury risk determined [23]. As such, daily rolling averages have been developed to provide a continuous method for assessing the ACWR [142, 143]. One study found no difference in injury risk by changing the acute:chronic time periods [141], although another [142] found a ratio of 3:21 days was the most sensitive for detecting periods of increased injury risk in elite players (R^2 = 0.76-0.82), which is greater than the 7:28 ratio (R^2 = 0.04-0.41) in studies using weekly rolling averages. An issue with this method however, is that all load is treated as equal, whereas fitness and fatigue decay over time, so training performed 3 weeks ago is less pivotal to a player's response to training than more recent training [147]. As such, exponentially weighted rolling averages have been used whereby a decreasing weighting factor is applied to older workloads [143, 147]. This model of exponentially weighted rolling average was more sensitive at explaining injury risk than regular daily rolling averages (R^2 = 87% *vs.* 21%), with total distance being the best variable for explaining increases in injury likelihood [143].

Taken together, players are required to tolerate high loads that are needed to develop physical qualities [131], which in turn protect against injuries [86, 87]. High chronic loads need to be achieved gradually in order to prevent spikes in load [23, 140, 142-144]. Unfortunately it is not as simple as preventing ACWR increasing above 2.0; there are numerous factors linked to injury risk, such as low body mass, poor aerobic fitness [86, 87], left-right movement asymmetry [148], previous injury [140] and in some [133, 145, 149], but not all cases [140, 144], younger training age. Newly drafted players (e.g. 1-2 years) should therefore have lower training and game loads compared to older players (e.g. 3-6 years) with gradual progressions as their physical characteristics develop [133, 149]. It is worth noting however, that whilst there are large increases in injury risk once the ACWR is greater than 1.5, the injury likelihood is still only ~2-6% in the studies reported [23, 143]. Practitioners may have to progress workloads at a faster rate in some players (e.g. player starts pre-season late, returns from injury, or misses sessions) and will have to weigh up the 'risk-reward' associated with larger increases in acute load relative to chronic load. Future research should manipulate training based on the ACWR to determine whether this reduces injury incidence.

The careful planning of training content and monitoring workloads associated with each drill and game in order to prevent spikes in loads, such as high-speed running, is vital [145]. During pre-season, average weekly loads in early pre-season in the region of 2700 AU or 20000 m have been reported [134], but can be as high as 7000 AU [135]. Loads should be gradually progressed over the course of pre-season [150], with total loads of 314-411 km reported over this period [133]. There are even models that can now be used to plan optimum loads for the pre-season period based on training load guidelines and performance goals [150]. In-season daily workloads are approximately 220-230 AU [132, 151] or 1500-2000 AU per week [134], with competitive games accounting for approximately half of weekly loads [134]. One study reported an average of 790 ± 182 AU per game [151], with more recent RPE loads closer to 1000 AU [132, 134, 144]. During the season, high load is positively associated with match outcome and performance, along with a positive training-stress balance for strain [57, 152]. As such, there is a conflict between maintaining sufficient load over the season, whilst at times providing recovery to dissipate fatigue. Coaches should be mindful of this and plan training mesocycles appropriately around important or ‘must win’ games. It is unclear whether open drills come with a higher physical load than closed drills [55, 153], and this is certainly dependent on the nature of the activity performed. Small-sided games (e.g. 9 *vs.* 9 or 14 *vs.* 14) on the other hand, can closely replicate the movement demands of match-play [154], and in some cases provide greater load per minute [153], which may provide an appropriate stimulus for developing technical, tactical and physical attributes simultaneously. More research is needed to understand the physical and skill demands of game-based training for AF players and how rule changes influence physical and technical demands.

There are a number of methods that can be used to monitor workloads, with both internal and external loads commonly quantified [155]. One study suggested that monitoring the internal response (e.g. RPE) whilst prescribing and adjusting training the external load (e.g. distance) optimises in-season workloads and performance, with these variables accurately predicting in-game performance [155]. There are numerous factors that influence the internal responses to training, with RPE being greater for ruckmen compared with midfielders (ES = 0.82), for less experienced players (ES = 0.44-0.52), and players with lower aerobic fitness, with a 0.2% increase in RPE load per 1 second increase in 3 km time trial time [156]. Session RPE and GPS variables share moderate to very-large correlations, with the strongest relationship seen with session distance (r = 0.77-0.88), although there is variation between players, with some players’ high-speed running having a greater impact on their RPE [156, 157]. Taken together with the different training modalities (e.g. resistance training, cross training, skills training) players will undertake, assessing both internal and external workloads is vital [155, 157]. There are a large number of GPS variables available; it is important that practitioners do not attempt to interpret or present each metric to the coach, yet still quantify the true training stress applied to the player. It is important to utilise variables that share some relationship with performance, injury and fatigue that are easily understood by players and coaching staff [143, 145, 158]. PlayerLoad™ (Catapult Innovations, Melbourne, Australia) is a reliable and valid metric (CV <2%) derived from proprietary software, which measures the accelerometer load a player records in a session and encompasses both running, non-running and short accelerative movements that are commonplace in AF training and competition [153, 159]. However, the strong relationship it shares with more easily interpreted variables such as total distance (r = 0.97) and high-speed running (r = 0.65) [156] raises questions its use in place of more traditional measures [155].

3.7 Training Interventions

Greater improvements in high-intensity running performance (Yo-Yo IRT) occur following training in the heat (29-33°C) [160], with large changes in performance observed after just 2 weeks (~20 hours) of training. These observations are confirmed by other studies in soccer and swimming [161, 162]. On the other hand, it seems that shorter (2.25 hours over 9 days) heat acclimation interventions, involving interval training on cycle ergometers, are less effective [163]. While partial adaptation to the heat was observed, heat training was no more effective than training in temperate conditions [163]. Current evidence suggests that whilst some adaptation to exercise in the heat can occur in 9 days, greater changes occur over a 2-week period, with longer exposure to heat (e.g. 20 hours), especially for changes in exercise performance. The reasons for these increases are not clear, but appear linked to systemic changes in haematocrit, plasma volume, and sweat rates, and these markers may provide valuable measures of heat acclimatisation, which shows large inter-individual differences [160].

Training in hypoxic conditions has also been used as an intervention in AF by elite clubs as part of pre-season training for a number of years. The exposure to altitude has varied, with different protocols used, such as live high, train high; live high, train low; and live low, train high using altitude chambers [164-166]. Following 19 days (RPE load = 14,254 AU; training time = 2047 min) of living and training at moderate altitude (2100 m), there was a greater increase in 2 km time trial performance (1.5%) and haemoglobin mass (2.8%) compared to the control group [164]. By 4 weeks post-camp, haemoglobin mass returned to baseline but time trial performance was maintained. Although the increase in haemoglobin mass is likely to influence the improvements in time trial performance, the higher training loads in the altitude group compared with the control would also have contributed [164]. There are similar responses to repeated exposure to altitude training when tracked over 2 pre-season camps, with increases of haemoglobin mass of 3.6 and 4.4% respectively [165]. The “responders” and “non-responders” varied between camps, indicating that adapting to altitude training does not appear to be an inherent trait and may vary from year-to-year depending on numerous factors. Maintaining body mass, avoiding illness and lower pre-training haemoglobin mass are important factors for beneficial responses to altitude training [165]. Intermittent hypoxic training induced improvements in Yo-Yo IRT performance but not 2 km time trial performance compared to a normoxic group following 4 weeks of high-intensity cycling sessions [166]. There was little change in haemoglobin mass over the training period, which could explain the reason for no improvement in time trial performance, where contributions from aerobic pathways are high [167]. However, improved Yo-Yo IRT performance, which taxes aerobic and anaerobic systems [168], could have been due to faster phosphocreatine resynthesis following the hypoxic training [169]. Overall, with sufficient exposure (≥13 days), hypoxic training (≥2000 m) appears to have a beneficial effect on running performance and haemoglobin mass, although some players do not respond favourably to hypoxia. Whilst there is a gradual decay in blood profiles in the 4-weeks post hypoxia, changes in running performance can be maintained.

The physiological changes following training in the heat are largely systemic [160], whereas training in hypoxic environments induces adaptations at the muscle level [170, 171]. Therefore, combining both forms of training could result in improved adaptations [172]. During a 2-week training camp in the heat, half the group were exposed to simulated hypoxic conditions in their rooms during the camp, and hypoxic cycling sessions (altitude = 2500-3000 m). Both groups showed large improvements in Yo-Yo IRT performance (~300 m, 44%) and exercise heart rate after the 14 days, with hypoxia creating no additional benefits. However, performance (Yo-Yo IRT) and physiological (blood volume, haemoglobin mass, and plasma volume) adaptations in the hypoxic and heat group appear to last longer following return from the camp compared to players just exposed to the heat [172]. As little as 170 hours of exposure to hypoxia in elite AF players is sufficient to induce erythropoiesis, which is greater 4-weeks post than immediately after the training camp. It is however worth noting that there are large inter-individual differences in the responses to training in the heat and hypoxia, and given the length of the season, it is unlikely that these transient increases in performance will have a large effect on performance.

3.8 Fatigue responses to training and competition

There are numerous monitoring protocols that have been used by practitioners to determine an athlete’s readiness for training and competition. Practitioners need to select a combination of tests that are based on sound theory, offer good reliability and validity, are time efficient for players and staff, and can inform practice in a timely manner. These have included wellness questionnaires [151, 173-176], single or multiple jumping protocols to measure force-velocity outputs [100, 177-182], power output from a 6 s cycle test [183], heart rate variability [173, 184], and blood or hormonal markers [72, 178, 179, 185, 186]. Whilst some blood and hormonal markers may be sensitive to changes in training load [179, 185] and influence performance [72], one study showed cortisol was not related to changes in training load or measures of physical performance [173]. Furthermore, the cost and invasive nature of these protocols make their long-term use somewhat limited. Heart rate variability also showed limited efficacy when compared with training load and changes in performance, whereas submaximal exercise heart rate appeared more effective [173] and can easily be used to monitor training responses [99]. Wellness questionnaires and jumping protocols incorporating the stretch-shortening cycle appear sensitive to changes in training load, as well as being related to match activity profiles and overall performance [173, 174, 176, 178]. As such, these protocols may prove useful in monitoring athletes' readiness for training and competition. Due to the multifactorial nature of fatigue [187], there is not one test that can be used to quantify the various types of fatigue the player may (or may not) be experiencing. A combination of subjective and objective tests assessing measures of performance (e.g. countermovement jump), physiological responses to workloads (e.g. submaximal exercise heart rate), and measures of wellbeing (e.g. questionnaires) is likely to encompass numerous manifestations of fatigue. Magnitude based statistical procedures such as z-scores, ES and likelihoods [188] can be easily used to determine any meaningful changes on an individual basis in any of these markers so practitioners are able to make informed decisions on players [189].

Following match-play specifically, there are reductions in muscle function [177-179, 182], increases in muscle damage [72], disturbances to hormonal levels [178, 179, 185, 186] and changes to perceptual measures of wellbeing and muscle soreness [151, 174] that typically last 24-72 hours, but little change in sleeping patterns [190]. Whilst this fatigue clears prior to the next scheduled game, neuromuscular fatigue [100, 180], markers of muscle damage [72], and reductions in perceived wellness [175] have the potential to negatively impact on activity profiles and technical match performance. As such, in addition to appropriate planning of each microcycle, practitioners may look to utilise interventions to accelerate the recovery process. Within AF players in particular, most recovery interventions have been shown to improve recovery. However, one study only showed perceptual measures of recovery were improved [191]. Others however, have shown positive effects of stretching, hydrotherapy, contrast water therapy, and cold-water immersion compared to control conditions [177, 181, 182]. In accordance with recent reviews, in terms of restoring muscle function, cold water immersion seems the most effective strategy, when compared to control or contrast water therapy [181, 182]; immersion times of 10-15 min at 10-15°C appear the most effective [181, 182, 192-194]. Physical qualities, such as aerobic fitness, may actually attenuate the fatigue response to competition in the first place [72], further highlighting the need for well-conditioned players.

Over the course of a season, players appear to cope with the rigours of training and competition, highlighted by a high testosterone-to-cortisol (T:C) ratio on 95% of testing points across an AFL season [178]. However, there may be periods of increased workloads, where immune function is compromised, which may leave players at an increased risk of illness [186]. When immune function, as measured by salivary immunoglobulin A, was tracked over a season at 36 hours post-match, there was a trend for compromised immune function at this time point, particularly as the season progressed [185]. This may suggest that as the season progresses, and fatigue accumulates, players' immune function is compromised and they are at an increased risk of illness; however, this is yet to be elucidated. Practitioners should be mindful of reduced immune function in the hours following a game, and this may become more of an issue in later stages of the season. Although a high T:C ratio is indicative of an anabolic environment, and reduced immune function may occur, it would also be useful to determine the impact this has on changes in physical characteristics over the course of a season as well as the incidence of illness.

4 Conclusions

The match demands of AF are complex, with numerous factors influencing player activities and performance. While high work-rates positively influence technical involvements, effective technical actions are most important to team success. Players must have the capacity to be able to perform the physical workloads required whilst being able to maintain their ability to execute technical skills under pressure and fatigue. Reductions in their ability to execute these skills effectively are likely to impede team performance. The physical demands of the game exceed those of other team field sports, with players having to cover in excess of 200 $m\cdot min^{-1}$ with 110 $m\cdot min^{-1}$ at high speed, during certain passages of play. As such, players need to be exposed to these intensities in training so they are prepared for the worst-case scenarios of competition. Combining these running intensities with match specific skills and scenarios is likely to develop a player's ability to read play and execute skills effectively under fatigue. Further research is required to gain a comprehensive understanding of the match demands of AFL. Identification of the physical and technical actions prior to key match events such as errors or goals is warranted to determine the mechanisms responsible for their occurrence.

Players need a broad range of physical qualities to be successful AF players, with speed, aerobic fitness, lean mass, muscular power and agility being vital. Newly drafted players must continue to develop these qualities over their career, and they may require up to three years of full-time training in order to be ready for the weekly rigours of an AFL season. Training and match loads must be progressed gradually though, particularly for these younger players, with sharp spikes in workloads being associated with increases in injury risk. Players appear to be able to tolerate these high training loads over the course of a season, with little change in chronic fatigue. Having said this, there may be points in the year, during periods of high loads or towards the end of the season where players are more susceptible to illness. With this in mind, staff should look to monitor the internal and external workloads of players in order to improve performance whilst minimising injury and illness risk.

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Figure Legends

Figure 1. Overview of the playing positions and field size in Australian football.

Figure 2. Flow chart of the studies selected for this review.

Tables

Table 1. Search terms used in each database. Searches 1 and 2 were combined with "AND".

Search 1	Search 2
"Australian football" OR "Australian rules football" OR "Australian football league"	"Match demands" OR "activity profiles" OR "running demands" OR "game demands" OR "running performance" OR physical OR fitness OR "aerobic capacity" OR "repeated-sprint ability" OR "anaerobic" OR "countermovement jump" OR "vertical jump" OR strength OR power OR speed OR sprint* OR agility OR "physical qualities" OR recovery OR fatigue OR "muscle damage" OR "training" OR "training load" OR "internal load" OR "external load".

Table 2. Physical match demands of Australian football across playing standards presented as weighted means, standard deviations and number of match files analysed.

Playing Standard	Playing time (min)	Distance (m)	Relative distance ($m \cdot min^{-1}$)	High-speed running (m)	Relative high-speed running ($m \cdot min^{-1}$)
Senior elite	101 ± 12 (n = 964)	12897 ± 1601 (n = 1017)	129 ± 13 (n = 985)	2560 ± 1327 (n = 402)	27 ± 11 (n = 786)
Youth elite	79 ± 17 (n = 22)	10929 ± 2578 (n = 14)	118 ± 19 (n = 135)	-	-
Senior sub-elite	108 ± 12 (n = 311)	13139 ± 1657 (n = 269)	123 ± 13 (n = 311)	-	29 ± 7 (n = 206)
Senior amateur	86 ± 15 (n = 78)	-	103 ± 16 (n = 78)	-	21 ± 7 (n = 78)
Youth amateur	74 ± 15 (n = 52)	-	88 ± 24 (n = 193)	-	12 ± 7 (n = 193)

The data reported are weighted means and standard deviations, with the raw data obtained from the following studies for senior elite (professional Australian Football League, AFL) [2, 10-12, 14, 16, 21, 24, 25]; youth elite (Under 16-18 state representatives) [16, 26, 27]; senior sub-elite (semi-professional: Western Australian Football League, WAFL; Victorian Australian Football League, VAFL; North Eastern Australian Football League, NEAFL) [11, 14, 17]; senior amateur [17]; youth amateur (Under 16-18) [28, 29].

Table 3. Description of technical skill involvements in Australian football.

Technical skill	**Description**
Kick	Disposing of the ball with any part of the leg below the knee including kicks off the ground
Handball	Disposing of the ball by striking it with a fist while it rests on the opposing hand
Disposals	Summation of kicks and handballs
Clanger	An error leading to an uncontested possession for the opposition
Contested possession	Possession obtained while in congested, and physically pressured situations
Uncontested possession	Possession obtained while a player is under no physical pressure from the opposition
Mark	When a player receives a kick that has travelled more than 15 m without it having touched the ground or another player impeding the ball
Hit-out	An action of clearing the ball from a ruck contest to a teammate by tapping the ball into space
Tackle	Using physical contact to prevent an opposition in possession of the ball from getting an effective disposal
Bounces	The number of bounces accrued while running with the ball
Inside 50	An action of moving the ball from the midfield into the forward 50 m zone

Table 4. Anthropometric and physical profiles of Australian football players across playing standards.

Variable	**Senior elite**	**Youth elite**	**Senior sub-elite**	**Senior amateur**	**Youth amateur**
Stature (m)	1.88 ± 0.07 (n = 311)	1.84 ± 0.07 (n = 4102)	1.84 ± 0.07 (n = 84)	1.82 ± 0.07 (n = 26)	1.80 ± 0.06 (n = 169)
Body mass	86.9 ± 8.5 (n = 311)	77.5 ± 8.5 (n = 4061)	83.6 ± 8.8 (n = 84)	85.9 ± 9.9 (n = 26)	72.8 ± 8.6 (n = 169)
Sum of 7 skinfolds (mm)	47.2 ± 7.7 (n = 40)	57.9 ± 15.9 (n = 2973)	57.60 ± 11 (n = 36)	-	-
Body fat (%)	8.2 ± 1.9 (n = 94)	8.3 ± 2.7 (n = 21)	13.7 ± 6.2 (n = 36)	-	-
Yo-Yo IRT level 2 (m)	1072 ± 236 (n = 151)	480 ± 194 (n = 24)	880 ± 260 (n = 14)	434 ± 118 (n = 26)	-
3 km time trial (sec)	648 ± 57 (n = 99)	672 ± 60 (n = 99)	712 ± 36 (n = 36)	-	-
20 m sprint (sec)	3.03 ± 0.12 (n = 85)	3.10 ± 0.11 (n = 3574)	3.22 ± 0.09 (n = 29)	-	3.10 ± 0.10 (n = 127)
Vertical jump (cm)	55.5 ± 5.4 (n = 92)	60.4 ± 7.5 (n = 3437)	48.9 ± 5.9 (n = 65)	51.2 ± 8.5 (n = 26)	59.8 ± 6.9 (n = 117)
1RM squat	127.3 ± 16.2 (n = 66)	121.0 ± 16.7 (n = 12)	-	-	-
1RM bench press	110.8 ± 11.8 (n = 67)	87.9 ± 12.7 (n = 21)	96.5 ± 16.6 (n = 22)	-	-

IRT = intermittent recovery test, RM = repetition maximum. The data reported are weighted means and standard deviations, with the raw data obtained from the following studies for stature and body mass: [17, 19, 20, 24, 26, 28, 41, 63, 79-81, 84, 86-96]; sum of 7 skinfolds [20, 26, 41, 63, 86, 88, 90, 97]; body fat percentage [19, 98]; Yo-Yo IRT level 2 [17, 24, 71, 91, 99, 100]; 3 km time trial [26, 63, 90]; 20 m sprint [20, 26, 28, 41, 79-81, 84, 88, 90, 92, 94, 96, 101, 102]; vertical jump [17, 19, 20, 41, 56, 79-81, 84, 86, 88, 94, 96, 101]; 1RM squat [89, 95, 103]; 1RM bench press [19, 97].