2021

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Callum J. McCaskie

Marc Sim

Robert U. Newton

Nicolas H. Hart

10.1016/j.ptsp.2021.08.006 McCaskie, C. J., Sim, M., Newton, R. U., & Hart, N. H. (2021). Lower-limb injury in elite Australian football: A narrative review of kinanthropometric and physical risk factors. *Physical Therapy in Sport*, *52*, 69-80. https://doi.org/10.1016/j.ptsp.2021.08.006

Physical Therapy in Sport 52 (2021) 69–80

Contents lists available at ScienceDirect

Physical Therapy in Sport

journal homepage: www.elsevier.com/ptsp

Lower-limb injury in elite Australian football: A narrative review of kinanthropometric and physical risk factors

Callum J. McCaskie [a, *], Marc Sim [a, c], Robert U. Newton [a, b], Nicolas H. Hart [a, b]

[a] School of Medical and Health Sciences, Edith Cowan University, Perth, WA, 270 Joondalup Drive, Joondalup, WA, 6027, Australia
[b] Exercise Medicine Research Institute, Edith Cowan University, Building 21, 270 Joondalup Drive, Joondalup, WA, 6027, Perth, Australia
[c] Institute of Nutrition Research, Edith Cowan University, 270 Joondalup Drive, Joondalup, WA, 6027, Perth, Australia

ARTICLE INFO

Article history:
Received 20 January 2021
Received in revised form
9 August 2021
Accepted 10 August 2021

Keywords:
Muscle
Bone
Overuse
Anthropometric

ABSTRACT

Objective: This review aims to provide a succinct and critical analysis of the current physical and mechanical demands of elite Australian football while examining lower-limb injury and the associated physical and kinanthropometric risk factors.
Methods: MEDLINE, PubMed, Web of Science and SPORTSDiscus electronic databases were searched for studies that investigated the playing demands, injury trends, and physical and kinanthropometric injury risk factors of elite Australian football. Articles from similar team sports including soccer and rugby (union and league) were also included.
Results: While the physical demands of elite AF have steadied over the past decade, injury rates continue to rise with more than two-thirds of all injuries affecting the lower-limbs. Body composition and musculoskeletal morphological assessments are regularly adopted in many sporting settings with current research suggesting high and low body mass are both associated with heightened injury risk. However, more extensive investigations are required to determine whether the proportions of muscle and fat are linked. Repeated assessment of musculoskeletal morphology may also provide further insight into stress fracture rates.
Conclusions: While kinanthropometric and physical attributes are highly valued within elite sporting environments, establishing a deeper connection with injury may provide practitioners with more insight into current injury trends.

1. Introduction

Injuries in team sports are a significant burden to athletes and sporting organisations, reducing performance and compromising a team's likelihood of success (Hoffman, Dwyer, Bowe, Clifton, & Gastin, 2020). Specifically, lower-limb injuries in elite Australian football (AF) clubs are estimated at $2.2 million annually in lost player wages (Hickey, Shield, Williams, & Opar, 2014). Practitioners, including physiotherapists, sport scientists, medical doctors and strength and conditioning specialists share a mutual goal of mitigating injuries. Thus, understanding the complex and dynamic nature of injury, along with the associated intrinsic (athlete related) and extrinsic (environmental) risk factors and inciting events are extremely important (Meeuwisse, Tyreman, Hagel, & Emery, 2007). This review aims to provide a critical review of AF, including the demands of the game and current injury epidemiology. Further, this review will examine several kinanthropometric and physical risk factors contributing to lower-limb injury in AF and similar team sports.

2. Methods

The scale for the assessment of narrative review articles (SANRA) has been considered in the preparation of this manuscript (Baethge, Goldbeck-Wood, & Mertens, 2019). Four electronic databases (PubMed, Web of Science, SPORTSDiscus and MEDLINE) were searched for original research, peer-reviewed articles involving AF (both elite and sub-elite). The search terms used were physical demands, running demands, injury epidemiology, injury risk factors, body composition, anthropometry, musculoskeletal, bone morphology, and physical attributes. No specific subject

* Corresponding author. Edith Cowan University, Perth, WA, 270 Joondalup Dr, Joondalup, WA, 6027, Australia.
E-mail addresses: c.mccaskie@ecu.edu.au, callummc@wce.com.au (C.J. McCaskie), marc.sim@ecu.edu.au (M. Sim), r.newton@ecu.edu.au (R.U. Newton), n.hart@ecu.edu.au (N.H. Hart).

https://doi.org/10.1016/j.ptsp.2021.08.006

characteristics were used to ascertain inclusion or exclusion criteria with both males and females included. Kinanthropometric and physical risk factors were also searched in similar team sports which included soccer and rugby (league and union) studies, as well as one hurling study. AFL injury data is published each year by the governing body (AFL, 2019) where they report on the incidence, prevalence and severity of all injuries that occur during the season. While the 2018 AFL injury report is presented, injury data from previous years has been referred to, as well as other AF injury epidemiology research.

3. Australian football

Australian football is a field-based sport played on grounds of 135–185 m in length and between 110 and 155 m in width (AFL, 2021c). AF is played across all participation levels from children to adults in males and females and has continued to grow in popularity every year (Saw et al., 2018). The Australian Football League (AFL) which is the elite male competition in Australia, involves 22 regular season matches followed by four weeks of finals (Orchard, Seward, & Orchard, 2013). In comparison, the newly established women's competition (AFLW) consists of nine regular season matches followed by a 3-week finals series. While most rules are identical across both competitions, AFLW matches are shorter in duration (15-min quarters compared to 20-min), have less players on the field (16 compared to 18) and have an extra interchange player (5 compared to 4). Specifically, the rules in the AFL have continued to evolve with the intention of reducing the risk of injury, and increasing player and spectator experience and enjoyment. Interchange rotations have been restricted to 75 per game, from being unlimited less than a decade ago, in a bid to slow the speed of the game to reduce injury rates (AFL, 2021a). A medical substitute has also been introduced to allow teams to keep their four interchange players even if a player suffers a game-ending injury (AFL, 2021b).

4. Demands of Australian football

4.1. Physical demands

While an AFL game usually lasts around 120 min (Ryan, 2019), elite AF players typically spend 100 min on the playing field (Coutts et al., 2015). AFL also has greater interchange freedom (75 interchanges per game) compared to rugby union (12 interchanges) (Rugby, 2021), rugby league (eight interchanges) (League, 2021) and elite top-division soccer (three substitutes) (FIFA, 2020). Movement patterns in the AFL were first assessed by time-motion analysis (Dawson, Hopkinson, Appleby, Stewart, & Roberts, 2004) where elite AF was described as intermittent with a combination of short high-intensity periods and longer periods of jogging and walking. However, time-motion analysis was replaced by global positioning system (GPS) technology in 2005, which was a more time-efficient method of measuring physical demands. Wisbey, Montgomery, Pyne, and Rattray (2009) reported GPS data from four consecutive AFL seasons (2005–2008) and found that 65% of total time was spent in a walk or jog (<8 km/h) with an average of 85 efforts above a speed of 18 km/h. Over the four investigated seasons, there was an increase (8.4%) in average velocity (m/min) with a drop (9%) in playing time. While total match distance hasn't changed since then, the volume of high-speed running (HSR) increased for a few years (2008–2010) with the large spike in interchange rotations (Janetzki, Bourdon, Norton, Lane, & Bellenger, 2021). This meant players were resting on the bench more frequently, potentially allowing them to produce more frequent high-intensity efforts thereafter (Janetzki et al., 2021). However, a substitute rule was introduced in 2011 with capped interchanges implemented in 2014 which has seen the physical game demands stabilise (Janetzki et al., 2021). AFL practitioners perceive sprinting at maximal speed and maximal acceleration as the two most common activities associated with hamstring strain injury (Freeman, Talpey, James, & Young, 2021). However, there is no standardised threshold or cut-off that represents sprinting or HSR in elite AF. Sprinting is commonly defined as a speed ≥24 km/h (Johnston, Murray, Austin, & Duthie, 2019; Varley, Gabbett, & Aughey, 2014), with HSR ranging from anything greater than 14.4 km/h, even up to greater than 24 km/h (Aughey, 2010; Coutts, Quinn, Hocking, Castagna, & Rampinini, 2010; Johnston, Murray, & Austin, 2019). Recent analysis of AFL match demands used >18 km/h for HSR and >24 km/h for sprinting, finding players covered ~1800m and ~255 m in those two zones respectively with a total match distance of ~13.2 km (Janetzki et al., 2021; Johnstonet al., 2019; Johnstonet al., 2019). Alternatively, AFLW players typically cover ~6.4 km per game (Thornton et al., 2020), of which ~370 m is > 18 km/h (Clarke et al., 2018). To sustain the physical demands of modern AF, high levels of aerobic fitness are required with elite AF players exhibiting a maximal oxygen uptake (VO_{2max}) of ~60 ml/kg/min (derived from 20-m multistage shuttle run) (Pyne, Gardner, Sheehan, & Hopkins, 2005; Young et al., 2005).

4.2. Mechanical demands

In AF, the ball is passed to teammates by players through hand (i.e. handball) or foot (i.e. kicking). The ability to kick the ball accurately and precisely to ensure it reaches a desired teammate or location without the opposition intercepting is crucial to success. In a study examining the influence of intermittent running on kicking accuracy in elite AF players (Young et al., 2010), fitter players (according to distance covered in a 2x2-minute run test) were 20.4% more accurate at kicking than the less-fit group. In 2014, lower-body strength and leg composition were assessed for their association with kicking accuracy in sub-elite AF players (Hart, Nimphius, Spiteri, & Newton, 2014). Players who were considered accurate kickers displayed greater strength in their support leg, while greater amounts of fat-free soft-tissue mass (FFSTM) and lower levels of fat mass of the lower-limbs were also associated with more accurate kicking.

Players are also required to change direction to baulk, evade opposition players and to chase their direct opponent. Improvement in agility has mainly developed from the application of small-sided games, due to the inherent cognitive and reactive elements involved, which has been shown to enhance the speed of decision-making (Young & Rogers, 2014). As AF players constantly react to different stimuli during competitive match-play, it is logical that reactive agility performance would also be conducive to match performance. Subsequently, higher performing (according to team selection) sub-elite AF players (state level seniors) were faster at completing a reactive agility test compared to their lower performing counterparts (state level reserves) (Sheppard, Young, Doyle, Sheppard, & Newton, 2006), despite no differences between players for a pre-planned change of direction test.

Jumping in AF is essential to catch (mark) the football, spoil (defend) the opposition's attempt to mark, or win possession from ball ups or throw-ins. The association between jumping and performance in AF has been investigated (Young et al., 2005; Young & Pryor, 2007), revealing that better performing players had significantly greater countermovement jump (CMJ) height under both loaded and unloaded conditions (Young et al., 2005; Young & Pryor, 2007). However, limitations of this work included that the jumps were performed off both feet and without a run-up, unlike jumps often performed in AF.

5. Injuries in Australian football

The AFL commenced surveying injuries in 1992, progressing to a comprehensive league-wide injury surveillance system in 1997, in order to methodically and systematically quantify and report injury rates (incidence, prevalence and recurrence) (Orchard & Seward, 2002). Over the last decade, injury incidence (number of new injuries, per club, per season) has been trending upward with an 11% increase from 2017 to 2018 (35.1–39.1 per club, per season) (Table 1) (AFL, 2019). This coincides with overall injury prevalence (number of missed matches per club, per season) which has been significantly higher in the last decade (151.5) compared to the decade before that (135.0). Despite this, the recurrence rate of injuries (same injury type on same side, within the same season) has decreased, which may be reflective of improved injury management practices or more conservative approaches.

While lower-limb injuries account for the majority of injuries in elite AF, the contact nature and high frequency of tackling and grappling mean that a percentage also occur to the upper body (Saw et al., 2018). Lower-limb injuries include areas of the legs and unilateral hip/groin regions whereas upper body injuries are defined as any injury of the head, neck, shoulder, arm, hand and torso regions. Shoulder injuries in particular are quite common due to the number of tackles and high-speed collisions (Hrysomallis, 2013). In 2018, upper-body injuries represented only 29.2% of all injuries in the AFL, compared to 70.8% of injuries to the lower-body (AFL, 2019).

6. Lower-limb injuries in elite Australian football

Regardless of playing level, the pelvis and lower-limbs remain the most commonly injured region in AF (Hrysomallis, 2013). In 2018, the incidence of lower-limb injuries in the AFL was 27.7 (AFL, 2019), of which 6.3 were hamstring-strains. The hamstring has been the most commonly injured body site in every AFL season since 1992, and subsequently, the most extensively researched (Opar et al., 2014; Ruddy et al., 2017). Hamstring strains have also accounted for 20.6 missed matches per club per season over the last two decades (Hoffman, Dwyer, Tran, Clifton, & Gastin, 2019). Risk factors including the volume of HSR (Duhig et al., 2016), linear kicking, and the frequency of collecting the ball from the ground may contribute to the high rate of hamstring injuries in AF (Opar et al., 2015; Saw et al., 2018). Monitoring the volume of HSR in particular has become a common hamstring injury mitigation strategy among AFL practitioners (Freeman et al., 2021) which may be due in part, to the large hamstring activation compared to gym-based hamstring exercises (van den Tillaar, Solheim, & Bencke, 2017). Despite increased hamstring-related research, incidence rates have remained fairly constant. No improvements have been seen in other injuries of the knee, hip/groin and thigh regions either, while greater incidence of shin/ankle/foot injuries have been observed over the last two decades (Hoffman et al., 2019). Despite the technological advancements and increased resources driven by research towards injury mitigation measures, lower-limb injuries in general have not evidentially decreased.

Despite their lower incidence rates, knee injuries have a very high severity (missed matches per injury occurrence) (Table 1). Anterior cruciate ligament (ACL) knee injuries in particular are generally season-ending with an average severity of 15.1 games in 2018. The incidence of ACL injuries have been relatively constant throughout the last two decades, with the occurrence of 0.7 per AFL club, per season (0.9 per club in 2018) (AFL, 2019; Orchard et al., 2013). Whilst the incidence of ACL injuries in the AFLW are similar to the AFL, AFLW players are more than six times more likely to sustain an ACL injury than their AFL counterparts (Fox, Bonacci, Hoffmann, Nimphius, & Saunders, 2020). Conversely, AFL players are four times more likely to sustain a hamstring injury than AFLW players (AFL, 2019; AFLW, 2019). Additionally, stress fractures of the leg and foot resulted in 8.66 missed matches per club across the 2018 season, which is comparable to 2017 (7.41) and 2015 (8.6) (AFL, 2017; Saw et al., 2018). While there is limited research surrounding the cause of stress fractures, there is some evidence to suggest they are training load related (repetitive stress) (Ekstrand & Torstveit, 2012), related to the playing surface (Warden, Creaby, Bryant, & Crossley, 2007) or related to diet (Heikura et al., 2018; Nieves et al., 2010). Stress fracture risk has been found to be highest in pre-season (Ekstrand & Torstveit, 2012), which may be due to a combination of many factors including the higher quantities of running volume (Colby, Dawson, Heasman, et al., 2017), warmer weather (which leads to harder grounds) (Twomey, Finch, Lloyd, Elliott, & Doyle, 2012), and the fact players are in the greatest energy deficit during this period (Bartlett et al., 2019).

Table 1
Incidence, prevalence, and severity of injuries in the AFL across season 2018. Adapted from AFL (2019).

Body Area	Incidence	Prevalence	Severity
Upper body			
Head	2.98	6.87	4.67
Neck	0.05	0.28	
Shoulder	2.21	7.87	3.26
Arm	0.00	0.00	3.03
Elbow	0.05	0.14	
Forearm	0.00	0.00	
Wrist	0.37	1.80	
Hand	1.08	2.64	
Trunk	0.56	1.57	2.58
Thoracic Spine	0.05	0.05	
Lumbar Spine	1.41	4.35	
Lower body			
Groin/Hip	3.30	11.27	3.03
Hamstring	7.35	28.03	3.00
Quadriceps	1.66	4.92	2.80
Calf	2.47	6.77	2.54
Knee	4.75	35.38	ACL = 15.11 MCL, PCL, LCL = 5.18 Other = 4.58
Leg	1.14	8.33	6.08
Foot	2.66	18.08	
Achilles	0.90	4.12	4.42
Ankle	3.55	15.63	4.03

Note: Incidence = number of new injuries, per club, per season; Prevalence = number of missed matches per club, per season; Severity = average number of missed matches, per injury occurrence; ACL = Anterior Cruciate Ligament; MCL = Medial Cruciate Ligament; PCL = Posterior Cruciate Ligament; LCL = Lateral Collateral Ligament.

7. Risk factors for lower-limb injury

Intrinsic and extrinsic risk factors can be further classified as modifiable (capable of being changed) and non-modifiable (unable to be altered) (Bahr & Holme, 2003; Fortington & Hart, 2021). In this review, we focus on modifiable intrinsic and extrinsic risk factors, as these can be influenced by athletes and practitioners. A summary of the categorisation of common injury risk factors are displayed in Fig. 1 (Fortington & Hart, 2021). A summary of articles investigating injury risk factors in elite AF is displayed in Table 2.

8. Modifiable intrinsic risk factors for lower-limb injury

8.1. Body composition

Body composition assessments have been used for many years in various populations to measure the proportions of water, fat and fat-free mass (bone, skeletal muscle, organs, connective tissue) (Borga et al., 2018; Prado & Heymsfield, 2014). In athletic populations, a combination of fat and fat-free regions are of interest as they provide an in-depth appraisal of nutrition status, metabolic balance and physical readiness (Borga et al., 2018; Prado & Heymsfield, 2014; Sutton, Scott, Wallace, & Reilly, 2009). Fat-free soft-tissue mass (FFSTM) (also known as lean mass) is used as a surrogate measure for muscle because it does not include fat or bone. Generally, high levels of FFSTM in athletes are deemed desirable due to their importance in physical components such as power, speed, and strength. Alternatively, high levels of fat mass are associated with impaired movement (Sutton et al., 2009) and kicking efficiency (Hart, Nimphius, Cochrane, & Newton, 2013; Hart, Nimphius, Spiteri, Cochrane, & Newton, 2016), and contribute towards faster onset of fatigue during aerobic and anaerobic activities (Collins, Silberlicht, Perzinski, Smith, & Davidson, 2014). Body composition can be measured via a range of different methods, including indirect estimates (body mass index [BMI], skinfolds, bioelectric impedance analysis), direct (total body water) and criterion methods (hydro-densitometry, dual-energy x-ray absorptiometry [DXA], magnetic resonance imaging, computed tomography) (Duren et al., 2008; Kuriyan, 2018) which are often performed at specific points in relation to a training program to assess the condition or readiness of an athlete (Bilsborough et al., 2015; Hart, Nimphius, Spiteri, et al., 2016; Sutton et al., 2009).

Mid-season body composition assessments were undertaken in elite AF players who displayed ~75 kg of FFSTM, representing 87% of their total body mass (Bilsborough et al., 2015). However, this is likely to fluctuate across the season depending on the volume and intensity of training with significant reductions seen in whole body fat mass and increases in %FFSTM over a pre-season phase in a similar cohort of athletes (Bilsborough, Greenway, Livingston, Cordy, & Coutts, 2016). Such findings are likely related to research reporting that elite AF players are in the greatest energy deficit across the pre-season phase (Bartlett et al., 2019). The end of an AFL pre-season has previously been identified as a period of highest injury incidence (Colby, Dawson, Heasman, et al., 2017), with 67% representing muscle strains or tears. Yet, the association with anthropometric factors has not been examined in elite AF and may provide further insight into this relationship.

Gastin et al. (2015) reported that elite AF players with low body mass experienced higher injury incidence and severity, citing greater body mass was likely important to protect the players from the frequent collisions during match play. In elite youth soccer, Kemper et al. (2015) highlighted that players with a BMI-increase of greater than 0.3 kg/m^2 within a month were at 61% higher risk of injury. Furthermore, 17–19 year olds with <5% body fat were at a 181% higher risk of injury compared to players with higher body fat percentage. While low body fat percentage seems advantageous in theory, performance and physiological function may be impaired if body fat is too low (Mascherini, Petri, & Galanti, 2015). Essential body fat is the fat present in bone marrow, nerve tissue and vital organs, and is required to sustain physiological function (Mascherini et al., 2015). Studies have found essential body fat

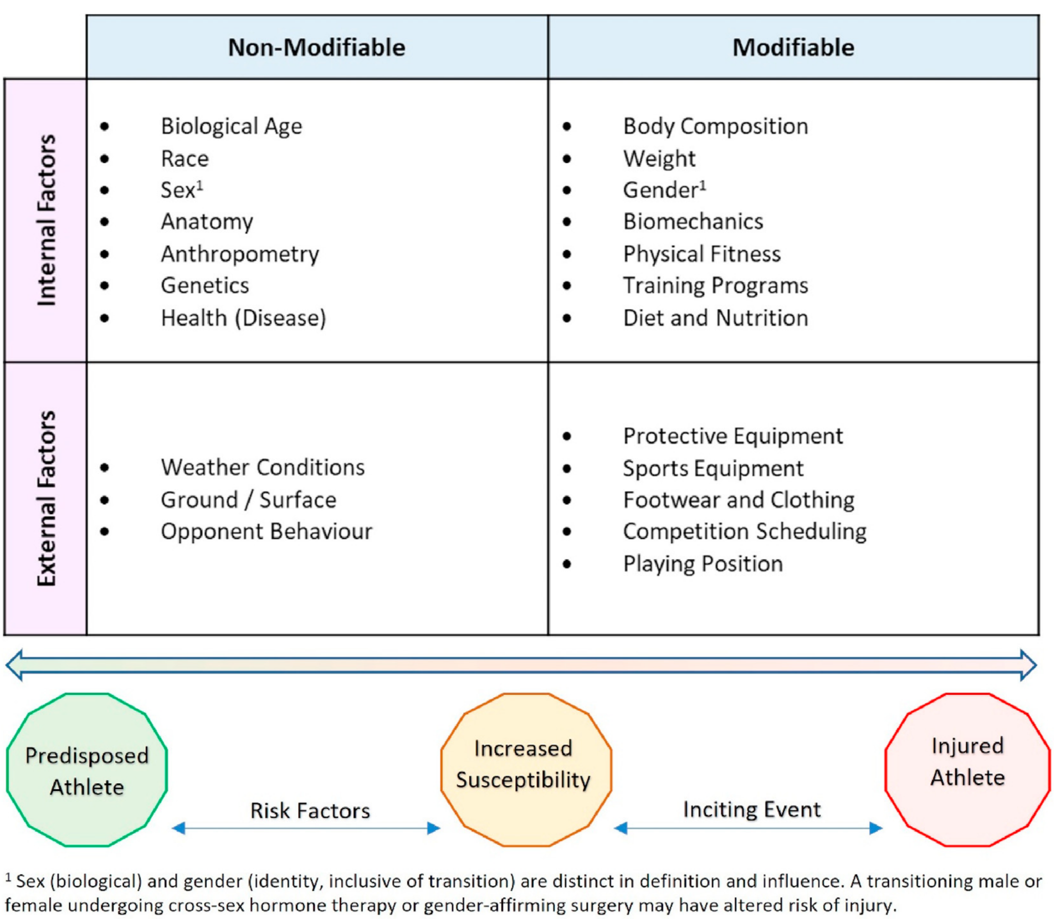

Fig. 1. Modifiable and non-modifiable, internal and external risk factors of lower-limb injuries that may increase athlete injury susceptibility across a continuum in response to an inciting event. Adapted from Fortington and Hart (2021).

Table 2
Summary of studies that have investigated injury risk factors in elite Australian football.

Study	N	Injury Type	Injury Definition	Risk factors examined	Predictors of Injury
Orchard (2001)	1607	Muscle strains	Incident which caused at least one game to be missed	Injury history; Age; Anthropometry; Weather; Season stage	- Previous injury was the biggest predictor of future injury - Greater risk with older age - Greater risk with higher BMI
Colby, Dawson, Heasman, Rogalski, and Gabbett (2014)	46	All injuries	Any injury which resulted in modified training or missed games	Training and game loads; Weekly loads	- Greater risk covering between 73.7 and 86.7 km over a 3-week period in pre-season compared to covering <73.7 km. - Greater risk covering <39.6 km over two weeks in-season than covering between 39.6 and 45.2 km.
Colby, Dawson, Heasman, et al. (2017a, b)	70	All injuries	Any injury which resulted in modified training or missed games	Training and game loads; Weekly loads; Seasonal loads	- Players aged 22–24 had greater risk than 20–21 year olds. - Greater risk covering <108 km in late pre-season compared to covering 125–164 km. - Greater risk during Rd1-Rd5 if players completed 76–88 km during the precompetition phase compared to covering 89–112 km.
Colby et al. (2018)	60	Non-contact lower body	Any injury causing a missed game	Exposure to max velocity; Training and game loads; Weekly load change	- Greater risk with exposure to 85% max velocity 0–8 times, 13–15 times and >15 times over an 8-week period compared to 11–12 times. - Greater risk with <599 m sprint accumulated over a 4-week period than >599 m
Rogalski, Dawson, Heasman, and Gabbett (2013)	46	All injuries	Any injury which resulted in modified training or missed games	Weekly loads; Training and game loads; Fortnightly loads; Weekly load change	- Greater risk completing >1750AU of load in 1-week compared to <1250AU. - Greater risk completing >4000AU in 2-weeks compared to <2000AU load. - Greater risk with weekly load change >1250AU compared to <250AU.
Sporri et al. (2019)	56	Non-contact lower body injuries	Damage to tissue of lower-body resulting in a missed game	Vertical stiffness; Seasonal change in vertical stiffness	- Greater risk with higher bilateral asymmetry in vertical leg stiffness at end of pre-season.
Murray, Gabbett, Townshend, Hulin, and McLellan (2017)	59	All non-contact injuries	Incident causing a missed training session or a missed game	Weekly loads; Monthly loads; ACWR	- Greater risk with in-season current week ACWR >2.0 for total distance compared to <0.49 and 0.5–0.99. - Greater risk with in-season current week ACWR >2.0 for high-speed distance compared to <0.49 and 0.5–0.99.
Gastin, Meyer, Huntsman, and Cook (2015)	69	All injuries	Any injury causing a missed game	Age; Height; Weight; 40 m sprint; Repeat-sprint; 6-min run; Vertical jump	- Greater risk with increased body mass - Greater risk with less 6-minute run distance - Greater risk playing in the forward position
Opar et al. (2015)	210	Hamstring injuries	Acute pain with MRI confirmation	Age; Anthropometry; Prior injury; Strength asymmetry; Eccentric hamstring strength	- Greater risk with less height and less body mass. - Greater risk with eccentric hamstring strength less than 256 N at start of pre-season and less than 279 N at end of pre-season.
Gabbe, Bennell, and Finch (2006)	135	Hamstring injuries	Clinical diagnosis	Anthropometry; Flexibility	- Greater risk with reduced Hip flexor flexibility in older players - Greater risk with higher weight in older players
Smith, Cameron, Treleaven, and Hides (2021)	125	Hamstring injuries	Acute pain resulting in missed match	Age; Anthropometry; Playing Exp; Injury history; Hamstring strength	- Greater risk for players older than 25 years - Greater risk for players who had hamstring injury in past 12 months - Greater risk for those with hamstring injury greater than 12 months prior - Greater risk with prior groin or prior calf injury
Orchard, Marsden, Lord, and Garlick (1997)	37	Hamstring injuries	Clinical diagnosis with missed match	Hamstring strength and power; Age; Anthropometry; Abdominal strength; Flexibility; Aerobic fitness; Injury history	- Greater risk with lower hamstring-to-quadriceps ratio at 60-deg/sec on Isokinetic dynamometer. - Greater risk with high hamstring torque asymmetry at 60-deg/sec. - Greater risk with lower hamstring peak torque at 60-deg/sec.
	164				- Greater risk with smaller multifidus muscle size

(continued on next page)

Table 2 (*continued*)

Study	N	Injury Type	Injury Definition	Risk factors examined	Predictors of Injury
Hides and Stanton (2017)		Lower-limb injuries	Condition preventing a player from completing the next training session or game	Age; Anthropometry; Position; Injury history; Muscle size	- Greater risk with small multifidus muscle size at L5 at start of pre-season. - Greater risk with larger Quadratus Lumborum at start of pre-season - Greater risk with smaller Multifidus muscle compared to Quadratus Lumborum.
Leung, Mendis, Stanton, and Hides (2015)	46	All injuries	Condition preventing a player from completing the next training session or game	Age; Anthropometry; Injury history; Lower back pain; Piriformis muscle size	- Greater risk for taller players - Greater risk for players with a decrease in cross-sectional area of piriformis across the season.
Stares et al. (2018)	70	Non-contact injuries	Any injury which resulted in modified training or missed games	Weekly loads; 4-week loads; ACWR;	- Greater risk with low 4-week (chronic) load for total distance, sprint distance and sRPE. - Greater risk with high ACWRs for total distance, sprint distance and sRPE.
Orchard, Chivers, Aldous, Bennell, and Seward (2005)	All AFL players 1992–2004	ACL injuries	No	Grass Type; Weather; Evaporation; Ground hardness	- Greater risk in AFL than VFL - Greater risk in games outside of Victoria - Greater risk with Bermuda Grass - Greater risk with high evaporation in previous month - Greater risk early in season

percentage in males is roughly 3–6% (Fleck, 1983; Friedl et al., 1994; Mascherini et al., 2015). As physical performance could be compromised with both high and low body fat, the optimal level may lie somewhere in the middle. Furthermore, semi-professional Icelandic soccer players who sustained groin strains had a 24% greater proportion of whole body fat than those players who avoided a groin strain (Arnason et al., 2004). Further, players who sustained hamstring strains had an 18% higher proportion of whole-body fat compared to those who did not sustain a hamstring injury. However, a more extensive examination into the compartmental proportions of muscle and fat of these players may have produced a stronger association with injury. Such hypotheses need to be confirmed by future research. Interestingly, peak oxygen uptake did not differentiate between injured and uninjured players. The proportions of muscle and fat in athletes, and the absolute volume of these tissues are important for physical performance (Perez-Gomez et al., 2008). Thus, a deeper analysis into absolute and relative body composition characteristics may expose a more refined connection with injury.

8.2. *Musculoskeletal morphology*

Mechanical strain from ground reaction forces (running and jumping), impact loading (kicking and tackles or collisions) and muscle-contractile forces can lead to bone deformation and microdamage if loading exceeds a particular threshold (Hart et al., 2017; Warden, Davis, & Fredericson, 2014). With adequate rest, bone is able to sufficiently repair itself, positively altering skeletal properties (size, shape, strength) with targeted remodelling (Hart et al., 2020). With insufficient rest, there is a chronic imbalance between the ability of the bone to repair itself due to an accumulation of microdamage. This can lead to the degeneration of bone tissue, causing a stress reaction, stress fracture or even a complete bone fracture (Warden, Burr, & Brukner, 2006; Warden et al., 2014). The specific area of bone which sustains damage is highly dependent on how an individual loads their bones. In athletic populations, long-distance runners normally use a rear-foot strike which tends to load the long bones of the leg (tibia, fibula and femur), whereas sprinters tend to adopt a forefoot strike which directs the load towards the bones of the foot (tarsals and metatarsals) (Warden et al., 2014). This mechanical hard-tissue strain can be moderated by soft-tissue with muscles of the lower-leg in particular, able to negate the risk of tibial and fibular stress fractures by neutralising bending forces (Romani, Gieck, Perrin, Saliba, & Kahler, 2002). Therefore, the assessment of musculoskeletal morphology in running-based athletic populations is important in mediating injury risk.

While DXA is the current gold standard to diagnose osteoporosis by measuring areal bone mineral density (aBMD) (Cummings et al., 1993), it is unable to obtain key bone parameters that also contribute to fracture risk (Sheu et al., 2011). The sensitivity and specificity of DXA-derived aBMD to predict fracture risk in athletes is less than 50% (Bouxsein & Seeman, 2009), suggesting the importance of other factors including bone structure and geometry represent the remaining strength capacity of bone (Hart et al., 2017). Specifically, increases to the internal and external diameter of long bone tissue exponentially increases its resistance to stress and strain from mechanical forces (Hart et al., 2017), which DXA is incapable of measuring (Stagi, Cavalli, Cavalli, de Martino, & Brandi, 2016). Peripheral Quantitative Computed Tomography (pQCT) however, provides a three-dimensional assessment of bone material, structure and geometry of macroscopic tissues (cortical and trabecular bone) in order to estimate bone strength in the appendicular skeleton (Sheu et al., 2011). High-resolution pQCT (HR-pQCT) is said to be even more accurate but remains unused in athletic populations as it typically only assesses bone at two sites (Cheung et al., 2013).

In an elite Rugby League cohort, bone structure changes were recorded over the course of 12-months from the start of the 2009 competitive season until the commencement of the 2010 season using pQCT (Georgeson, Weeks, McLellan, & Beck, 2012). Players had their kicking leg evaluated at various sites of their tibia which are thought to be common areas of loading (4%, 14% and 38% - distal to proximal) together with the maximal circumference of the triceps surae (66%; gastrocnemius and soleus) muscle group (Crossley, Bennell, Wrigley, & Oakes, 1999). While some changes in bone structure were evident, no association was observed for any bone morphological indicators and injury. However, Rugby League running volumes are significantly less than AF, with sport-specific activities considerably more bilateral in nature (i.e. less kicking and jumping). Thus, it is highly unlikely Rugby League athletes would be representative of AF players due to different physiological and mechanical demands. Nevertheless, previous research in the elite rugby codes have identified that significant differences exist between forwards and backs with regards to body mass, fat mass, lean mass and bone mineral content (BMC) (Harley, Hind, & O'Hara J, 2011; Jones et al., 2018; Lees et al., 2017). However, this study only investigated group changes and failed to account for individual player changes. Hence, it is unreasonable to suggest that group changes would be reflective of individual changes as these individual changes may provide a greater insight into injury risk.

Researchers are yet to examine longitudinal bone structure changes in AF players, with only cross-sectional snapshots of AF players' bone characteristics at the beginning of a season (Hart et al., 2016, 2020a). Hart et al. (2020a) examined the differences in material, structural and strength properties of bone between kicking and support (non-kicking) legs in an elite Australian football cohort. This work highlights that the support leg had superior bone characteristics, including greater bone mass, greater trabecular, cortical and total cross-sectional areas and thicker cortices than the kicking leg. Greater bone morphological outcomes of the support leg are hypothesised to be from exposure to different functional demands and increased frequency of high and odd-impact axial loading (Hart et al., 2017). A similar study investigated the differences in bone characteristics of the lower-leg between experienced (>3 years in elite AF) and inexperienced (≤3 years in elite AF) players (Hart et al., 2016). Experienced players exhibited superior bone characteristics including significantly greater tibial mass, cortical area, cortical thickness while also displaying greater muscle cross-sectional area and less area of fat mass than their less experienced counterparts. While lower-limb injury was not investigated, the bone characteristics used have been previously linked with stress fracture (Hart et al., 2017), which may suggest that younger, less experienced AF players are at an increased risk of injury (Fortington et al., 2016).

Due to the high-running demands and intermittent nature of Australian football, players are subjected to high loading of bones of the lower-limbs and feet. With an increasing number of stress fracture injuries in the AFL (AFL, 2019), the ability to assess key musculoskeletal morphological characteristics throughout a season will help improve the load management decisions of club practitioners. Through an evaluation of the available literature there is a distinct lack of research investigating longitudinal and seasonal changes in bone characteristics, particularly in team sport athletes. While the vast majority of bone-related injuries likely stem from overuse scenarios, repeated assessment of bone characteristics in high-risk athletes may provide greater understanding of the types and volumes of load that place hard-tissue at risk and inform the development of future preventative or remedial programs.

8.3. Physical performance characteristics

Similar to body composition, evaluating physical performance characteristics (speed, agility, muscle strength, muscle power, aerobic capacity) is common in athletic populations. This allows practitioners to gauge athlete readiness at specific timepoints of their season or to determine the effectiveness of a training program. Superior muscular strength characteristics are typically associated with greater performance in general sporting actions such as changing direction, jumping and sprinting (Lehance, Binet, Bury, & Croisier, 2009; Suchomel, Nimphius, & Stone, 2016). Greater physical performance characteristics have also been shown to differentiate between higher and lower performing athletes for a given sport (Gleim & McHugh, 1997; Suchomel et al., 2016). Hence, athletes who display superior physical characteristics give themselves or their respective team a greater chance of success. Furthermore, there is increasing evidence that superior physical performance characteristics are also associated with less injury (Case, Knudson, & Downey, 2020; Opar et al., 2015).

8.4. Muscular strength and power

Strength and power training form key components of any athletic conditioning program with overwhelming evidence showing strength characteristics transfer to physical performance and general sporting skills (Suchomel et al., 2016). Moreover, there is increasing evidence strength plays a crucial role in injury mitigation (Lauersen, Bertelsen, & Andersen, 2014). A systematic review from 2014 examined the efficacy of various training modalities on injury reduction (Lauersen et al., 2014). Strength training was the most effective training modality at mitigating injury, reducing sports injuries by up to 68% and overuse injuries by 47%. Compared to other exercise modalities, strength training was better at mitigating injury than proprioception training and stretching. While strength training interventions did not involve AF players, the heterogenous sample used may suggest that well-designed progressive strength training programs may provide players broad protection from injury in many sports. Division 1 male collegiate athletes who sustained a lower-limb injury had 15% lower relative barbell squat strength than those athletes who remained uninjured (Case et al., 2020). Noteworthy, for every 10 Newton (N) increase in eccentric knee flexor strength, the risk of hamstring injury was reduced by 6.3% (early pre-season) and 8.9% (late-pre-season) in elite AF players (Opar et al., 2015). What is unknown, however, is how much absolute or relative lower-body strength is associated with lower-limb injury in elite Australian football.

8.5. Speed and repeat-sprint ability

Speed and anaerobic running performance have also been considered when examining the relationship between workload and injury or performance (Gastin, Fahrner, Meyer, Robinson, & Cook, 2013; Malone, Hughes, Doran, Collins, & Gabbett, 2019). This was seen in elite AF for a repeat sprint protocol which was able to differentiate between selected and non-selected players for the first game of a competitive season, with selected players displaying superior repeat sprint ability (Le Rossignol, Gabbett, Comerford, & Stanton, 2014). Alternatively, slower hurling athletes over 5, 10 and 20-m had more than a three times greater injury risk than faster players (Malone et al., 2019). This finding was also mirrored with regards to repeat sprint ability (6 × 35-m shuttles). Hurlers who completed the repeat sprint shuttles in over 36.5 s were at a five times greater injury risk (particularly at the lower-limb) compared to those athletes who completed the test in under 30 s. Interestingly, elite AF players with poor repeated sprint ability coped well with training load and showed improved match performance (according to an algorithm based on accumulated match statistics) with higher weekly workload volumes. Comparatively, those AF players with better repeated sprint ability displayed decreased match performance when exposed to increased training loads (Gastin et al., 2013). These differences are likely due to the different physical match demands in hurling and AF and the differences in standard of competition. Near-maximal velocity exposure has also been linked with non-contact injury risk in elite AF. Four or less exposures to 85% of individual max velocity over a four-week period was associated with two times higher risk of injury than those exposed to 85% max velocity five to eight times over a four-week period (Colby et al., 2018). While it is evident that maximal speed and repeat-sprint are important factors in AF, the extent to which they are associated with injury has not been fully established.

8.6. Aerobic capacity

Aerobic capacity is considered one of the most important physical aspects of elite AF due to the sports' large running component (Mooney et al., 2011). Thus, it is vital that players display a certain level of aerobic fitness in order to perform at the elite level. Subsequently, if players are under-prepared for the physical demands of the sport, they place themselves at a higher risk of injury (Gabbett, 2016). This was seen in a group of elite AF players with inferior 6-min run time associated with greater injury risk (Gastin et al., 2015). Heightened aerobic capacity is also linked with a superior ability to resynthesise creatine phosphate, which is heavily depleted during repeat sprints, a common action in AF (Gray & Jenkins, 2010). However, without enhanced neuromuscular efficiency, fatigue can set in, altering the way in which match running is accumulated (Mooney, Cormack, O'Brien, Morgan, & McGuigan, 2013). Further to this, neuromuscular efficiency allows athletes to tolerate fatigue, produce high amounts of power and have greater running propulsion, resulting in less energy expenditure for an equivalent task (Dolci et al., 2018). Aerobic fitness was also highlighted as an important attribute for recruitment into the AFL (Robertson, Woods, & Gastin, 2015) and differentiated between higher and lower performing players in elite junior AF (Young & Pryor, 2007). This may allow players with greater aerobic fitness to cover more ground and have a greater impact on the game. Thus, enhanced aerobic capacity is likely to result in athletes experiencing less fatigue and greater movement efficiency, which in turn, may reduce their risk of injury.

9. Modifiable extrinsic risk factors for lower-limb injury

9.1. Exercise workload

While most extrinsic risk factors in AF are non-modifiable (Bahr & Holme, 2003), exercise workload, particularly at the elite level, is meticulously planned to maximise the fitness and performance of athletes, while reducing their risk of injury. Exercise workload (also known as training load) can be grouped into internal (physiological or subjective) and external load (objective work completed) (Gabbett, 2016) with both forms used collectively to accurately depict the athletes' responses to an exercise workload stimulus.

Currently, evidence supports the concept that both high and low exercise workloads are associated with greater injury risk, suggesting that optimal exercise workload prescription is somewhere in the middle (Cross, Williams, Trewartha, Kemp, & Stokes, 2016; Dennis, Farhart, Goumas, & Orchard, 2003). Adopted by many team sports, rating of perceived exertion is a commonly used method of assessing internal exercise intensity (McCaskie, Young, Fahrner, & Sim, 2019). Recently, the modified category ratio 10-point scale has been used which is traditionally multiplied by session duration to form a universal loading score, measured in arbitrary units (AU). An elite AF team adopted this method, examining the association between weekly exercise workload and injury risk (Rogalski et al., 2013). It was discovered that players with an in-season weekly exercise workload greater than 1750 AU were at a 244% greater risk of injury than players undertaking weekly exercise workloads less than 1250 AU. Furthermore, players exposed to week-to-week changes of in-season workload greater than 1250 AU had a 258% greater risk of injury compared to those players exposed to a week-to-week change of less than 250 AU.

In a bid to avoid these spikes in exercise workload, many sports practitioners have adopted the acute chronic workload ratio (ACWR) based on a model originally proposed by Bannister and colleagues (Banister, Calvert, Savage, & Bach, 1975). This fitness-fatigue model illustrates that an exercise workload stimulus results in both a longer term ‘fitness’ and short term ‘fatigue’ state. Based on this model, the ACWR was initially proposed as a model which could predict injury and has been implemented in many different sports including AF (Carey et al., 2017), soccer (Bowen, Gross, Gimpel, Bruce-Low, & Li, 2019), rugby league (Hulin, Gabbett, Lawson, Caputi, & Sampson, 2016) and cricket (Hulin et al., 2014). Using total distance as an indicator of exercise workload (via GPS technology), elite AF players with an ACWR greater than 2.0 were at a 5–8 times greater risk of injury than those players with an ACWR less than 0.49 or between 0.50 and 0.99. Similarly, elite soccer players playing in the English Premier League were at a 5–7 times greater risk of injury with an ACWR greater than 2.14 for total distance. However, since 2018, flaws in the statistical methodologies and study designs of the ACWR have been raised (Fanchini et al., 2018; Wang, Vargas, Stokes, Steele, & Shrier, 2020). While it may have application in prescribing training load, its use in predicting injury has been strongly criticised, with the Australian Institute of Sport (AIS) discouraging the use of the ACWR in early 2020 (AIS, 2020).

However, absolute loads (total distance in particular) are still regularly adopted to assess external workload, especially in those sports that involve a large proportion of running. In recent years, this information has been derived from GPS. As GPS has evolved and become more accurate, more research has arisen linking external workload variables derived from this technology with injury (Colby et al., 2014; Colby, Dawson, Heasman, et al., 2017; Jaspers et al., 2018). In an elite AF cohort, players completing three-week pre-season total distances of 73.7–86.7 km were at a 549% greater risk of injury than those players who completed less than 73.7 km (Colby et al., 2014). Additionally, four-week in-season total distance less than 75.1 km and sprint distance less than 599 m was associated with increased risk of injury in a similar group of elite AF players. Similarly, players who accumulated significantly more high-speed running distance (>24 km/h) above their two-yearly average over a four week period had almost two times greater risk of hamstring injury than those players who did not (Duhig et al., 2016). Recently, researchers have gone one step further, exploring the use of multivariate modelling (Colby, Dawson, Peeling, et al., 2017; Cummins et al., 2019) and machine learning (Carey et al., 2018; Ruddy et al., 2018) to better understand the risk factors surrounding injury. However, like much of the literature in elite sport, small injury event numbers have reduced the statistical power of these models. Regardless, running based sports like AF have provided evidence that external and internal exercise workload variables are common risk factors for injury and cannot be ignored.

10. Recommendations and future directions

It is widely acknowledged that injury etiology is complex and multifactorial (Bittencourt et al., 2016). Thus, mitigation strategies are becoming holistic in nature (Meeuwisse et al., 2007). The assessment of kinanthropometric and physical characteristics are widely adopted in sporting clubs globally to measure the readiness and status of athletes. However, increasing awareness that these characteristics may also be important to mediate injury risk may encourage future research to conduct these more routinely. It has been speculated that higher body mass is desirable for AF players due to the frequent collisions and high contact nature (Gastin et al., 2015). However, high fat mass is seen to impair physical performance (Sutton et al., 2009) and reduce kicking accuracy (Hart et al., 2013; Hart, Nimphius, Spiteri, et al., 2016). Thus, it appears that there may be an optimal ‘zone’ for AF players. Subsequently, future research should consider undertaking regular body composition and musculoskeletal morphological assessments to examine if injury risk is affected by changes in kinanthropometric characteristics. Forthcoming explorations could also assess the association between physical characteristics and injury. Collectively, these findings may provide practitioners with insight into fitness status and injury susceptibility. As low injury numbers may reduce the statistical power with single club investigations, researchers should be encouraged to utilise multiple clubs or even a league-wide surveillance.

11. Conclusion

Modern physical and mechanical demands of elite Australian football continue to generate high rates of lower-limb injuries. While players are expected to cover ~13 km on average per game, they are also required to accelerate, decelerate, jump, change direction, and tackle opposition players, exemplifying the wide array of possible injury mechanisms. While injuries continue to plague AF at all levels, injuries of the lower limb are the most prevalent. As some lower-limb injury risk factors are non-modifiable (age, previous injury, gender), other risk factors are modifiable through specialised practice and targeted intervention. Specific to body composition, lower fat mass and higher lean mass appear favourable for health and performance. Additionally, body mass appears to be associated with injury in AF players. However, the extent to which the proportions of muscle and fat are involved in this relationship has not been fully established. Similarly, it seems logical that musculoskeletal morphology and its relationship with injury are examined more extensively with the upward trend of overuse and bone injuries in AF. Furthermore, the relationship between exercise workload and injury has been examined comprehensively. However, more research is needed to develop a stronger link between injury and the physical attributes which underpin the ability to accumulate load. Consequently, the examination of risk factors collectively with lower-limb injury may provide further insight into this relationship within elite Australian football.

Ethical approval

None declared.

Ethical approval

Not applicable.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors have no conflict of interest to declare.

Acknowledgements

Marc Sim is supported by a Royal Perth Hospital Research Foundation Career Advancement Fellowship.

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