Accelerometer and GPS-Derived Running Loads and Injury Risk in Elite Australian Footballers

Marcus J. Colby,[1,2] Brian Dawson,[1,2] Jarryd Heasman,[2] Brent Rogalski,[2] and Tim J. Gabbett[3,4]

[1]*School of Sport Science, Exercise and Health, The University of Western Australia, Perth, Australia;* [2]*West Coast Eagles Football Club, Perth, Australia;* [3]*School of Exercise Science, Australian Catholic University, Brisbane, Australia; and* [4]*School of Human Movement Studies, The University of Queensland, Brisbane, Australia*

Abstract

Colby, MJ, Dawson, B, Heasman, J, Rogalski, B, and Gabbett, TJ. Accelerometer and GPS-derived running loads and injury risk in elite Australian footballers. *J Strength Cond Res* 28(8): 2244–2252, 2014—The purpose of this study was to investigate the relationship between overall physical workload (global positioning systems [GPS]/accelerometer) measures and injury risk in elite Australian football players ($n = 46$) during a season. Workload data and (intrinsic) injury incidence were monitored across preseason and in-season (18 matches) phases. Multiple regression was used to compare cumulative (1-, 2-, 3-, and 4-weekly loads) and absolute change (from previous-to-current week) in workloads between injured and uninjured players for all GPS/accelerometer-derived variables: total distance, V1 distance (total distance above individual's aerobic threshold speed), sprint distance, force load, velocity load, and relative velocity change. Odds ratios (ORs) were calculated to determine the relative injury risk. Cumulative loads showed the strongest relationship with greater intrinsic injury risk. During preseason, 3-weekly distance (OR = 5.489, $p = 0.008$) and 3-weekly sprint distance (OR = 3.667, $p = 0.074$) were most indicative of greater injury risk. During in-season, 3-weekly force load (OR = 2.530, $p = 0.031$) and 4-weekly relative velocity change (OR = 2.244, $p = 0.035$) were associated with greater injury risk. No differences in injury risk between years of Australian Football League system experience and GPS/accelerometer data were seen. From an injury risk (prevention) perspective, these findings support consideration of several GPS/accelerometer running load variables in Australian football players. In particular, cumulative weekly loads should be closely monitored, with 3-weekly loads most indicative of a greater injury risk across both seasonal phases.

Key Words odd ratios, injury prevention, load monitoring, team sports

Address correspondence to Marcus Colby, marcus_colby@hotmail.com.

28(8)/2244–2252

Journal of Strength and Conditioning Research

Introduction

The objectives and game structure of Australian football are similar to those of soccer, being described as a running game combining athleticism with speed and requiring skillful foot and hand passing (9). In addition to high movement demands, acts of bumping, tackling, and "wrestling" opposition players when contesting a mark or ground ball adds a challenging physical aspect to the game. At the elite (national competition) level, where movement demands and intensities are greater than in state leagues or junior competitions (1,3), injury risk is high, with both intrinsic (internal; overuse, overexertion) and extrinsic (external; collision, contact) injuries being commonly reported (14,16). An upward trend in injury prevalence in the past decade in Australian football (14) has prompted great interest in the multifactorial aspects of injury prevention. Training "overload," where training stress is not balanced by adequate recovery, is often attributed as an important (although largely preventable) cause of injury (particularly soft tissue) (7,8,15,16). Therefore, monitoring training and game workloads and other variables such as player wellness scores to (potentially) reduce injury risk is of great importance to professional sporting teams (8,16).

In recent years, the use of global positioning systems (GPS) and accelerometers in team sports has rapidly increased. In particular, teams in the Australian Football League (AFL) have extensively applied these new technologies to both game and training environments (2,10,19). For example, GPS data have provided in-depth information on activity profiles of athletes, including objective measures such as total distance, distances traveled within velocity bands, and average movement speed (2,10,19). However, the full potential of this athlete monitoring system (compared with other methodology) is yet to be fully explored, especially from an injury prevention perspective. Furthermore, relatively few studies have explored the relationship between physical workload and injuries (6,7,15,16).

Rogalski et al. (16) used session ratings of perceived exertion (RPE) to analyze training and game loads in AFL players from 1 club across a whole season. Larger 1-weekly (odds ratios: ORs = 3.38) and 2-weekly (OR = 4.74) cumulative loads, and week-to-week absolute change in load from the previous to the current week (OR = 2.58), were associated with a greater injury risk throughout the in-season (competition) phase. Furthermore, players with 2–3 and 4–6 years of AFL system experience had a significantly lower injury risk compared with >7 year players (OR = 0.22, OR = 0.28). These results emphasize the importance of carefully assessing workloads, both in a cumulative weekly manner and also through week-to-week load changes. Additionally, with RPE scores, the sensation of fatigue may be elevated during submaximal tasks (13). Therefore, adding workload quantification through GPS and accelerometer measures to RPE scores can provide a more complete range of workload assessment variables and may prove to be more useful.

Piggott et al. (15) used GPS variables (total distance and distance above 12 $km \cdot h^{-1}$) as measures of training load in elite Australian football players, reporting that corresponding spikes (>10% change) in weekly training load explained ~40% of illness and injury in the subsequent 7 days. However, this study was limited to a small sample ($n = 16$) over a 15-week preseason phase and analyzed only individual workload gradients from one week to the next.

In rugby league, Gabbett and Ullah (7) recently used GPS variables to quantify workload in 36 elite players across 117 training sessions. Interestingly, when only >9 m of sprinting per session was performed, a 2.7 times greater relative risk of injury was observed than when no or lower amounts of sprinting were completed. Although the sprinting demands of Australian football are likely to be greater than reported for rugby league (3,19), these results do demonstrate a relationship between the amount of sprinting performed and lower-body soft tissue injury risk. Therefore, GPS/accelerometer variables measuring high-speed running and force actions may be important predictors of injury risk.

Greater player workloads have commonly been recorded in AFL games when compared with subelite and junior matches (1,3,17). Therefore, it is important to carefully manage a young newly recruited player because their less mature bodies may be unable to cope with the initial training and game demands of the AFL environment. Junior (under 18) players have been shown to be 7.7 and 5.8 kg lighter in body mass and lean mass, respectively, than AFL players (17). Additionally, greater bone mineral content and density was noted in the AFL players used for comparison (17); such bone remodeling and structural adaptation are likely because of greater workloads experienced at the elite level. This finding underscores the need to identify appropriate workloads for different player groups, as the amount of experience in the AFL system may play a key role in coping with training and game loads.

The application of GPS/accelerometer data for load monitoring and injury prediction and prevention is yet to be fully explored. This study aimed to examine the relationship between physical workload (GPS/accelerometer) measures and injury risk in elite AFL players across a season. It was hypothesized that very high absolute workload values, plus very large increments from 1 week to the next, would significantly increase injury risk.

Methods

Experimental Approach to the Problem

Each day a player was involved in a training session or game, and their previous 1-, 2-, 3-, and 4-weekly individual loads were calculated. Based on the work of Rogalski et al. (16), relationships between workloads and injury were then investigated in 2 different ways. First, the likelihood that accumulated load (over 1–4 weeks) could contribute to an injury at a later date was considered by examining any link between 1-, 2-, 3-, and 4-weekly cumulative loads and subsequent injury. Second, whether a large increment in load between successive weeks contributed to an injury was also explored, by analyzing the week-to-week change between the current and previous week's total loads. Particular emphasis was placed on the intrinsic (rather than extrinsic and total) injuries recorded, as these are more directly related to soft-tissue injuries, especially from a training-load perspective (6).

Subjects

Data were collected from elite Australian footballers ($n = 46$) from 1 AFL club. Their mean age, stature, and body mass were 25.1 ± 3.4 years, 188.0 ± 6.8 cm, and 87.0 ± 8.2 kg, respectively. Players competed in matches within the AFL or Western Australian Football League (WAFL) competition during the 2012 season. Within the squad, 12 players had 1–2 years, 19 had 3–6 years, and 15 had >7 years of AFL system experience. All data were obtained from the club's database, but without any identifying player information. Ethical approval was obtained from the Human Research Ethics Committee of The University of Western Australia.

Procedures

Workload was quantified through GPS/accelerometer units, with data collected from any session (training or game) in which a player undertook a running load. The GPS units (SPI Pro X; GPSports, Canberra, Australia), which incorporate a tri-axial accelerometer, were placed on the back of players (between the scapulae) in either a pocket sewn into the player's jumper or in a fitted GPSports harness. These GPS units were sampled at an interpolated rate of 15 Hz (true sampling at 5 Hz), and the accelerometers at 100 Hz. After each session, the data were downloaded into a specialized analysis program (TEAM AMS–release 1.9 2012).

On occasions ($n = 334$ of 3,601; 9%) where a player had not worn a GPS/accelerometer unit during a running session, not participated in certain drills, or the data were deemed unreliable because of an intermittent signal (<6 "locked on" satellites), data were predicted, as follows:

- Main training session data: predicted by calculating individual player (positional) averages for drills completed.
- Rehabilitation session data: predicted using rehabilitation drill averages for drills completed.
- Game data: predicted using individual season game averages (from 18 matches) while taking into consideration the time spent on ground.

Several authors have found that the accuracy of GPS technology for measuring movement demands of athletes to be very good (4,11,12). Recently, sprint performance and accelerometer variables have also been reported as reliable measures (10,18); however, caution should still be taken when interpreting sprint distance results (11). The variables below were selected for this study because of their relevance to running loads (and potential injury) and their <10% coefficient of variation, as reported by Hiscock et al. (10) and Waldron et al. (18). Some variables are taken directly from GPSports (Team AMS) software, whereas others are derived from a separate data analysis package (Athletic Data Innovations [ADI]).

GPSports (TEAM AMS):

- Distance = total distance covered (m): this includes walking, jogging, fast running, and sprinting.
- Sprint distance = total distance covered (m) above 75% of the individual player's maximum speed, as determined from preseason 20-m sprint (electronic timing gates) tests (where available) or GPS game data.

Athletic Data Innovations GPS-derived data:

- V1 distance = total distance covered (m) above the individual player's aerobic (blood lactate ~2 $mmol \cdot L^{-1}$) threshold speed, as determined from a preseason incremental speed (1% gradient) treadmill running test to exhaustion. The term "aerobic threshold speed" is used by the GPS software, which analyzed the data. Commonly, individual player V1 speeds were between 12.5 and 14.5 $km \cdot h^{-1}$.
- Velocity load = a measurement of running power and momentum. The more continuous and higher the velocity equates to a higher velocity load.
- Relative velocity change (RVC) load = a calculated function (algorithm) of accelerations, decelerations, and changes of direction, which are summed together to produce an overall "acceleration load" value.

TABLE 1. Session type averages for season phases.*†

Session type	Preseason	In-season (Mean load per session)	Whole-season
Rehab			
Distance (m)	7,139 (6,897–7,383)	6,575 (6,270–6,907)	6,935 (6,734–7,136)
V1 distance (m)	‡3,455 (3,341–3,563)	3,045 (2,903–3,183)	3,306 (3,218–3,394)
Sprint distance (m)	148 (122–178)	97 (73–122)	130 (110–149)
Force load (AU)	518 (483–572)	454 (428–480)	495 (464–526)
Velocity load (AU)	‡827 (799–855)	724 (692–755)	789 (768–811)
RVC load (AU)	3.54 (3.31–3.80)	3.46 (3.12–3.82)	3.51 (3.30–3.72)
Main training			
Distance (m)	‡10,302 (10,154–10,472)	7,205 (7,096–7,325)	9,184 (9,061–9,308)
V1 distance (m)	‡2,808 (2,741–2,875)	1,522 (1,478–1,569)	2,344 (2,290–2,397)
Sprint distance (m)	‡160 (150–171)	90 (85–96)	135 (128–142)
Force load (AU)	‡787 (773–801)	579 (569–589)	712 (701–722)
Velocity load (AU)	‡943 (926–961)	606 (595–617)	821 (808–835)
RVC load (AU)	‡11.5 (11.28–11.72)	8.5 (8.28–8.72)	10.42 (10.24–10.59)
AFL game			
Distance (m)	9,420 (8,838–10,000)	§13,399 (13,150–13,644)	12,554 (12,281–12,827)
V1 distance (m)	3,059 (2,863–3,275)	§4,091 (3,984–4,201)	3,872 (3,769–3,975)
Sprint distance (m)	200 (178–222)	§268 (254–283)	253 (241–266)
Force load (AU)	766 (715–815)	§1,133 (1,108–1,155)	1,055 (1,030–1,080)
Velocity load (AU)	1,003 (935–1,069)	§1,406 (1,377–1,433)	1,320 (1,290–1,351)
RVC load (AU)	11.91 (11.17–12.58)	§16.87 (16.46–17.27)	15.82 (15.41–16.22)
WAFL game			
Distance (m)	10,573 (8,975–11,886)	§12,348 (12,027–12,661)	12,183 (11,853–12,513)
V1 distance (m)	3,562 (3,018–4,014)	§4,267 (4,121–4,401)	4,201 (4,062–4,341)
Sprint distance (m)	220 (171–265)	259 (242–277)	256 (239–272)
Force load (AU)	822 (706–924)	§966 (1,237–1,310)	953 (922–984)
Velocity load (AU)	1,080 (917–1,219)	§1,274 (1,237–1,310)	1,256 (1,219–1,294)
RVC load (AU)	10.94 (9.28–12.56)	§13.74 (13.29–14.16)	13.48 (13.04–13.92)

*AFL = Australian Football League; WAFL = Western Australian Football League; AU = arbitrary units; V1 = aerobic threshold speed; RVC = relative velocity change.
†Data are expressed as mean (95% confidence intervals).
‡Preseason ($p < 0.001$) significantly greater load than in-season.
§In-season ($p < 0.001$) significantly greater load than preseason.

(Both these variables are measured in arbitrary units [AU]).

Athletic Data Innovations accelerometer-derived data:

- Force load = a cumulative measurement that sums the forces produced from both foot strikes and collisions. Higher speed running will correspond with higher force load values, reflecting a measure of the "number" and "intensity" of foot strikes (i.e., total g-force from foot strikes). In addition, physical contact through collisions and jumping forces will also contribute to force load values.

(This variable is measured in AU).

Data were collected in both the preseason and in-season (competition) phases. Movement demands and running loads were typically higher (≈5 "on-legs" sessions per week) during the preseason (late November to March), as players trained to improve their fitness capacities. The in-season phase, where fitness maintenance and match availability took priority, generally consisted of 2 "on-legs" training sessions per week, plus games. This phase (March–September) was limited to 18 matches (rather than 22) for data collection because of changes in the training schedule that restricted data availability in the lead up to finals.

Injury information was classified by the club's senior physiotherapist, collated, and then updated in the club's database. Injuries were classified as being either: low severity (the player was given modified training and did not miss a game), and/or moderate severity (the player missed 1–2 weeks of training and missed 1–2 games), and/or high severity (the player missed >2 weeks of training and missed >2 games) (16). Injuries were also categorized by injury type (description) and body site (injury location). The mechanism in which a player acquired an injury was also classified, as being intrinsic (internal; overuse, overexertion) or extrinsic (external; collision, contact) in nature (6,14,16), with only intrinsic injuries being considered with respect to injury risk.

Statistical Analyses

The analysis was performed in a similar manner to the previous work of Gabbett (6) and Rogalski et al. (16). Injury incidence was calculated by dividing the total number of injuries by the "on-legs" exposure time and reported as rates per 1,000 training and game hours. Injury data were analyzed per 1,000 (combined) training and game hours, and χ^2 analysis compared the frequency of injuries between preseason and in-season periods. A multiple regression model was used

Table 2. Workload data for different years of AFL system experience for season phases.*†

	Preseason	In-season	Whole-season
Distance (m)			
1–2 y	350,674 (313,731–387,616)	344,088 (299,321–388,855)	694,762 (629,839–759,685)
3–6 y	375,136 (339,277–410,995)	373,924 (354,243–393,605)	749,060 (705,808–792,312)
>7 y	356,431 (316,662–396,200)	‡320,417 (262,034–378,800)	676,848 (597,150–756,547)
V1 distance (m)			
1–2 y	§‖99,883 (90,090–109,676)	99,574 (81,572–117,577)	199,458 (180,025–218,890)
3–6 y	§120,903 (111,984–129,822)	106,281 (96,846–115,716)	227,184 (211,123–243,245)
>7 y	§113,757 (100,480–127,034)	92,534 (78,612–106,457)	206,292 (182,857–229,727)
Sprint distance (m)			
1–2 y	‖4,322 (2,756–5,888)	5,753 (3,770–7,735)	10,075 (6,645–13,506)
3–6 y	7,480 (6,048–8,930)	7,170 (6,330–8,010)	14,660 (12,649–16,671)
>7 y	5,848 (4,900–6,796)	¶4,076 (2,819–5,332)	9,924 (8,393–11,454)
Force load (AU)			
1–2 y	26,890 (23,474–30,307)	26,787 (23,090–30,483)	53,677 (47,792–59,563)
3–6 y	28,043 (25,370–30,716)	29,814 (27,067–32,560)	57,857 (53,445–62,269)
>7 y	27,613 (23,322–31,904)	26,798 (20,973–32,622)	54,411 (45,668–63,154)
Velocity load (AU)			
1–2 y	31,608 (27,192–36,025)	31,446 (27,078–35,814)	63,055 (56,000–70,109)
3–6 y	36,475 (33,386–39,565)	36,117 (34,011–38,224)	72,593 (68,545–76,641)
>7 y	35,898 (31,536–40,260)	32,281 (26,404–38,159)	68,180 (59,331–77,029)
RVC (AU)			
1–2 y	365 (324–407)	385 (321–450)	751 (663–839)
3–6 y	386 (321–452)	440 (396–384)	827 (733–920)
>7 y	345 (290–399)	¶347 (251–443)	692 (567–817)

*AU = arbitrary units; RVC = relative velocity change.
†Data are expressed as mean (95% confidence intervals).
§Preseason load significantly greater than in-season ($p \leq 0.05$).
‖1–2 y significantly lower load than 3–6 y ($p \leq 0.05$).
¶>7 years significantly lower load than 3–6 y ($p \leq 0.05$).

Table 3. Classification of preseason and in-season injuries.*

	Preseason (1,405.8 h)			In-season (1,700.4 h)			Overall (3,106.2 h)			Preseason vs. in-season	
	N	Injury incidence	%	*N*	Injury incidence	%	*N*	Injury incidence	%	χ^2	*p*
	110	78.2 (63.6–92.9)	37.0	187	110 (94.2–125.7)	62.96	297	95.6 (84.7–106.5)	100	8.102	0.004
Site											
Thigh	44	31.3 (22.1–40.5)	40.0	57	33.5 (24.8–42.2)	30.5	101	32.5 (26.2–38.9)	34.0	0.12	0.732
Hip/groin	11	7.8 (3.2–12.4)	10.0	7	4.1 (1.1–7.2)	3.7	18	5.8 (3.1–8.5)	6.1	1.83	0.177
Knee	6	4.3 (0.9–7.7)	5.5	13	7.7 (3.5–11.8)	7.0	19	6.1 (3.4–8.9)	6.4	1.43	0.231
Pelvis/low back	9	6.4 (2.2–10.6	8.2	15	8.8 (4.4–13.3)	8.0	24	7.7 (4.6–10.8)	8.1	0.58	0.445
Head/neck	6	4.3 (0.9–7.7)	5.5	20	11.8 (6.6–16.9)	10.7	26	8.4 (5.2–11.6)	8.8	5.16	0.023
Ankle/foot	12	8.5 (3.7–13.4)	10.9	32	18.8 (12.3–25.3)	17.1	44	14.2 (10.0–18.4)	14.8	5.74	0.017
Lower leg	9	6.4 (2.2–10.6)	8.2	22	12.9 (7.5–18.3)	11.8	31	10.0 (6.5–13.5)	10.4	3.29	0.070
Shoulder/arm/elbow	6	4.3 (0.9–7.7)	5.5	10	5.9 (2.2–9.5)	5.3	16	5.2 (2.6–7.7)	5.4	0.39	0.533
Abdomen											
Chest/ribs/upper back	1	0.7 (−0.7–2.1)	0.9	2	1.2 (−0.5–2.8)	1.1	3	1 (−0.1–2.1)	1.0	0.17	0.678
Forearm/wrist/hand	6	4.3 (0.9–7.7)	5.5	9	5.3 (1.8–8.8)	4.8	15	4.8 (2.4–7.3)	5.1	0.17	0.682
Injury type											
Muscle strain	55	39.1 (28.8–49.5)	50.0	54	31.8 (23.3–40.2)	28.9	109	35.1 (28.5–41.7)	36.7	1.19	0.275
Haematoma/contusion	21	14.9 (8.5–21.3)	19.1	63	37 (27.9–46.2)	33.7	84	27 (21.3–32.8)	28.3	13.91	0.000
Joint injury	22	15.6 (9.1–22.2)	20.0	40	23.5 (16.2–30.8)	21.4	53	17.1 (12.5–21.7)	17.8	2.39	0.122
Fracture/dislocation	4	2.8 (0.1–5.6)	3.6	9	5.3 (1.8–8.8)	4.8	13	4.2 (1.9–6.5)	4.4	1.10	0.294
Concussion	4	2.8 (0.1–5.6)	3.6	9	5.3 (1.8–8.8)	4.8	13	4.2 (1.9–6.5)	4.4	1.10	0.294
Laceration	1	0.7 (−0.7–2.1)	0.9	6	3.5 (0.7–6.4)	3.2	7	2.3 (0.6–3.9)	2.4	2.71	0.100
Other	3	2.1 (−0.3–4.5)	2.7	6	3.5 (0.7–6.4)	3.2	9	2.9 (1.0–4.8)	3.0	0.52	0.472
Mechanism											
Intrinsic	62	44.1 (33.1–55.1)	56.4	72	42.3 (32.6–52.1)	38.5	134	43.1 (35.8–50.4)	45.1	0.06	0.814
Extrinsic	48	34.1 (24.5–43.8)	43.6	115	67.6 (55.3–80.0)	61.5	163	52.5 (44.4–60.5)	54.9	16.45	0.000
Severity											
Low (1)	84	59.8 (47.0–72.5)	76.4	154	90.6 (76.3–104.9)	82.4	238	76.6 (66.9–86.4)	80.1	9.54	0.002
Moderate (2)	14	10 (4.7–15.2)	12.7	24	14.1 (8.5–19.8)	12.8	38	12.2 (8.3–16.1)	12.8	1.09	0.297
High (3)	12	8.5 (3.7–13.4)	10.9	9	5.3 (1.8–8.8)	4.8	21	6.8 (3.9–9.7)	7.1	1.20	0.274
Activity performed											
Game	24	17.1 (10.2–23.9)	21.8	165	97 (82.2–111.8)	88.2	189	60.8 (52.2–69.5)	63.6	80.87	0.000
Training	86	61.2 (48.2–74.1)	78.2	22	12.9 (7.5–18.3)	11.8	108	34.8 (28.2–41.3)	36.4	51.50	0.000

*Mean injury incidence reported per 1,000 on-legs training and game hours (95% confidence intervals).

Table 4. Injury incidence and AFL system experience.*†‡

Playing experience (y)	Preseason	In-season	Whole-season
		Injury incidence (per 1,000 h)	
1–2 ($n = 12$)	71.5 (40.3–102.7)	101.3 (70.7–131.9)	86.4 (65.3–107.5)
3–6 ($n = 19$)	86.8 (55.8–117.6)	107.6 (83.8–131.5)	97.2 (78.3–116.1)
>7 ($n = 15$)	87.3 (46.6–127.9)	113.6 (73.6–153.5)	100.4 (73.2–127.6)

*AFL = Australian Football League.
†Data are expressed as mean (95% confidence intervals).
‡No significant differences were found in injury incidence for AFL system experience.

to compare cumulative and absolute change in workloads between injured and uninjured players for all GPS/accelerometer variables. For each variable, the data cases were split into 3 even groups, with the first (low load) group used as the reference group for analysis. Odds ratios were calculated to determine the injury risk at a given cumulative workload or for absolute change in workload from the previous to current week. When an OR was greater than 1, an increased risk of injury was reported (i.e., OR = 1.50 is indicative of a 50% increased risk) and vice versa. For an OR to be significant, 95% confidence intervals (CIs) did not contain the null OR of 1.00. Multiple regression was also used to analyze player groupings of 1–3 years, 4–6 years, and >7 years of AFL system experience, to explore any differences in workloads due to this factor. The >7 years group was used as the reference group for analysis. Data were analyzed using IBM SPSS Statistics 20.0 and reported as means and 95% CI. Significance was accepted at $p \leq 0.05$. Based on a total of 297 injuries (intrinsic + extrinsic) from 3,601 player-sessions (i.e., 46 players participating in 79 training and game sessions across the whole season), the calculated statistical power to establish the relationship between running loads and injury risk was ≥90%.

Table 5. Preseason training and game load risk factors for intrinsic injury in elite Australian footballers.*

Load calculation	OR Exp (B)	95% CI Lower	95% CI Upper	Significant p
Cumulative load (sum)				
3-weekly velocity load				
<6,737 AU (reference)	1.00			
6,737–8,046 AU	0.239	0.062	0.92	0.037†
>8,046 AU	0.368	0.068	1.994	0.246
3-weekly sprint distance				
<864 m (reference)	1.00			
864–1,453 m	0.229	0.054	0.966	0.045†
>1,453 m	3.667	0.884	15.214	0.074
3-weekly distance				
<73,721 m (reference)	1.00			
73,721–86,662 m	5.489	1.572	19.164	0.008†
>86,662 m	1.115	0.125	9.944	0.922
Absolute change (±)				
Sprint distance				
<(−) 49 m (reference)	1.00			
(−) 49–155 m	0.356	0.099	1.278	0.113
>155 m	3.284	0.915	11.784	0.068
Force load				
<(−) 13 AU (reference)	1.00			
(−) 13–556 AU	2.772	0.757	10.157	0.124
>556 AU	0.096	0.009	1.037	0.054
RVC load				
<0.1 AU (reference)	1.00			
0.1–9.4 AU	0.04	0.004	0.393	0.006†
>9.4 AU	1.25	0.265	5.881	0.778

*OR = odds ratio; CI = confidence interval; AU = arbitrary units; RVC = relative velocity change.
†$p \leq 0.05$.

Results

Training Loads

Average training loads for preseason were significantly ($p < 0.001$) greater than in-season for all GPS/accelerometer variables (distance, V1 distance, sprint distance, force load, velocity load, and RVC load). Similarly, the average V1 distance and velocity load during rehabilitation training sessions were significantly ($p < 0.001$) greater for preseason than in-season. Game running loads

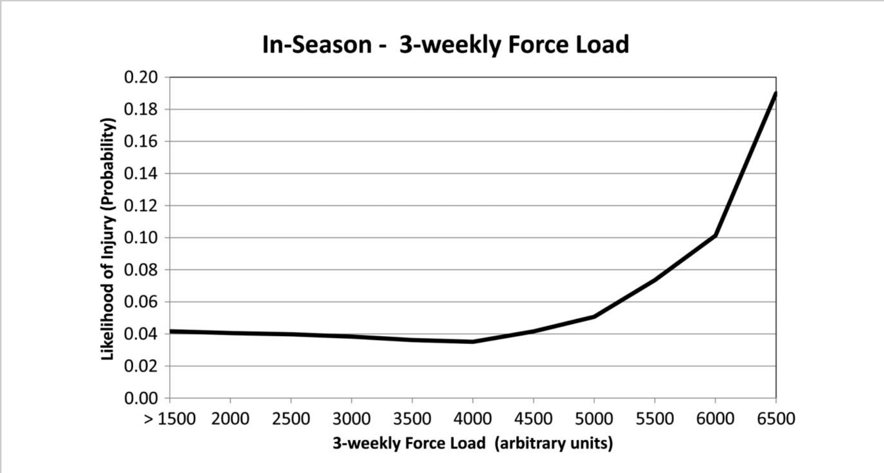

Figure 1. Injury probability in-season as 3-weekly force load (cumulative) increases.

Table 6. In-season training and game load risk factors for intrinsic injury in elite Australian footballers.*

Load calculation	OR Exp (B)	95% CI Lower	95% CI Upper	Significant p
Cumulative load (sum)				
1-weekly velocity load (AU)				
<1,927 (reference)	1.00			
1,927–2,387	0.685	0.311	1.509	0.347
>2,387	1.901	0.745	4.853	0.179
3-weekly force load (AU)				
<4,561 (reference)	1.00			
4,561–5,397	1.518	0.716	3.218	0.277
>5,397	2.53	1.091	5.871	0.031†
4-weekly RVC load (AU)				
<84 (reference)	1.00			
84–102	1.417	0.688	2.919	0.345
>102	2.244	1.057	4.765	0.035†
2-weekly V1 distance (m)				
<10,321 (reference)	1.00			
10,321–12,867	0.407	0.2	0.829	0.013†
>12,867	0.276	0.11	0.689	0.006†
2-weekly distance (m)				
<39,618 (reference)	1.00			
39,618–45,257	0.426	0.204	0.891	0.024†
>45,257	0.423	0.173	1.033	0.059
Absolute change (±)				
Distance (m)				
<−549 (reference)	1.00			
−549 to 6,955	0.492	0.248	0.977	0.043†
>6,955	0.477	0.207	1.096	0.081

*OR = odds ratio; CI = confidence interval; AU = arbitrary unit; V1 = aerobic threshold speed; RVC = relative velocity change.
†$p \leq 0.05$.

for all variables were significantly ($p < 0.001$) greater for in-season than for preseason practice matches for both AFL and WAFL competitions (Table 1). Regarding AFL system experience, players with >7 years had significantly ($p \leq 0.05$) lower total distance, sprint distance, and RVC load values during in-season than 1–3 and 4–6 year players (Table 2).

Injury Incidence

Injury incidence increased ($\chi^2 = 8.102$, df = 1, $p = 0.004$) from preseason (78 per 1,000 hours) to in-season (110 per 1,000 hours) (Table 3). The thigh (33 per 1,000 hours, 30.5%) and ankle/foot (19 per 1,000 hours, 17.1%) were the most common sites of injury during the in-season, with the most common type of injury being hematomas/contusions (37 per 1,000 hours, 33.7%) and muscle strains (32 per 1,000 hours, 28.9%). Extrinsic injuries were significantly ($\chi^2 = 16.45$, df = 1, $p = 0.000$) greater during in-season (68 per 1,000 hours) than preseason (34 per 1,000 hours). Injury incidence during in-season was lowest for 1–2 year players (101 per 1,000 hours) and highest for >7 year players (114 per 1,000 hours); however, no significant differences were found between any of these player groupings (Table 4).

Likelihood of Intrinsic Injury With Different Training Loads

For both seasonal phases, accumulated workloads (primarily 3-week) were found to have the greatest association with intrinsic injury risk.

Preseason

In preseason, 3-weekly total distances between 73,721 and 86,662 m were found to be associated with a greater injury risk when compared with <73,721 m (OR = 5.489, 95% CI = 1.57–19.16, $p = 0.008$). Conversely, a 3-weekly velocity load of between 6,737 and 8,046 AU recorded a lower injury risk when compared with <6,737 AU (OR = 0.239, 95% CI = 0.06–0.92, $p = 0.037$). Although a 3-weekly sprint distance between 864 and 1,453 m was shown to have a lower injury risk when compared with <864 m (OR = 0.229, 95% CI = 0.05–0.97, $p = 0.045$), a 3-weekly sprint distance >1,453 m was also shown to have a greater injury risk when compared with <864 m (OR = 3.667, 95% CI = 0.88–15.21, $p = 0.074$). Finally, a previous to current weekly change in RVC load between 0.1 and 9.4 AU recorded a lower injury risk when compared with <0.1 units (OR = 0.040, 95% CI = 0.004–0.393, $p = 0.006$) (Table 5).

In-season

A 3-weekly force load of >5,397 AU recorded a greater injury risk when compared with <4,651 AU (OR = 2.53, 95% CI = 1.09–5.87, $p = 0.031$). Figure 1 demonstrates the increase in injury probability as 3-weekly force load increases. A 4-weekly RVC load >102 AU had a higher injury risk when compared with <84 AU (OR = 2.244, 95% CI = 1.06–4.77, $p = 0.035$). Conversely, a 2-weekly V1 distance of >12,867 m was associated with a lower injury risk when compared with <10,321 m (OR = 0.276, 95% CI = 0.11–0.69, $p = 0.006$). Similarly, 2-weekly total distances between 39,618 and 45,257 m recorded a lower injury risk when compared with <39,618 m (OR = 0.426, 95% CI = 0.20–0.89, $p = 0.024$). Additionally, a previous to current weekly change in distance within −549 to 6,955 m was shown to have a lower injury risk when compared with less than −549 m (OR = 0.492, 95% CI = 0.25–0.98, $p = 0.043$) (Table 6).

Discussion

This study is the first to investigate the relationship between training and game loads (derived from GPS/accelerometer data) and injury risk in elite Australian football. For all measured variables, training load was greater during the preseason phase, where fitness improvements and skill development take priority, in comparison to the in-season, where games are played weekly and where the injury incidence was significantly higher. The careful management of training running loads, to balance those exerted during games, is an on-going challenge for strength and conditioning staff.

In contrast to previous reports (15,16), this study identified a number of GPS/accelerometer running load variables that were significant intrinsic injury predictors during the preseason phase. Here, a 3-weekly distance between 73 and 86 km was associated with a 5.5 times greater intrinsic injury risk when compared with distances of <73 km. Similarly, 3-weekly sprint distances of >1,453 m recorded a trend ($p = 0.074$) for a greater (3.7 times) injury risk, compared with <864 m. However, in contrast, a 3-weekly sprint distance of 864–1,453 m was associated with a significantly lower injury risk. These contrasting results support previous literature (7), in not only highlighting the fine balance between restricting training loads for injury prevention purposes but also prescribing sufficient loads to adequately prepare players for game demands. It is important to acknowledge that although excessive training loads may increase intrinsic injury risk, insufficient loads may achieve the same outcome, with a certain level of load (in-between an underload and overload) likely to be protective for injury. Finally, in contrast to previous literature regarding preseason injury risk in Australian footballers (16), this study found no relationship between absolute change in load from the previous to current week and subsequent injury. The reasons for these divergent findings are not clear and were unexpected in this study.

During the in-season phase, exerting a 3-weekly force load of >5,397 AU was associated with a 2.5 times greater injury risk when compared with <4,561 AU. Similarly, exerting a 4-weekly RVC load of >102 AU was associated with a 2.2 times greater injury risk when compared with <84 AU. In contrast (and as was found with the preseason results), a 2-weekly distance of 39–45 km was associated with a lower (0.5 times) injury risk than <39 km. Similarly, a 2-weekly V1 distance of >12,867 m was associated with a 0.7 times lower injury risk than <10,321 m. These findings suggest a protective effect of certain (moderate) load levels. Gabbett and Ullah (7) have recently reported that the relative risk of soft-tissue injury is lower in elite rugby league players who cover more distance at lower intensities, consistent with the contention that moderate running loads and intensities may offer some protection against intrinsic injury.

Musculoskeletal immaturity of players with less AFL system experience has been hypothesized to be associated with an increased injury risk when they are exposed to elite training and game loads (17). However, in our study, no significant relationships were found between GPS/accelerometer-derived running loads and injury risk for 1–2 year players when compared with other years of AFL system experience (3–6 years, >7 years). Perhaps, because of the strict load modification strategy of 1–2 year players used within the club studied here, overall injury incidence was slightly lower (NS: 86/1,000 "on-legs" hours) in this group. Preseason V1 and sprint distance running loads were also lower for this group than for 3–6 year players, but not different for the >7 year players, who, in turn, had lower total distance and sprint distance loads in-season than the 3–6 year players. Injury risk was slightly greater (NS: 114/1,000 "on-legs" hours) for the >7 year grouping during the in-season, but whether the running load data reflect a deliberate management practice by the club or reflects less training load because of slightly more injuries occurring is unclear. We have previously shown a higher in-season injury risk in this playing group using load data based on RPE values (16), and future studies should aim to analyze multiple seasons of data to further investigate any effect of experience in the AFL system (and in other sports) on running load-injury relationships. The players' injury history used here was also not considered, and this is recognized as an important factor in subsequent injury incidence (5,14). Thus far, there is some evidence to suggest that the careful management of players, both on entering the elite system and when in the latter stages of their career, may potentially assist in reducing injury risk (5,6,14,16).

In this study, a total of 9% of GPS data were predicted, primarily because of unit malfunction caused by poor/intermittent satellite signal reception. Future advances in technology, including enabling data collection in roofed stadiums, plus greater player compliance in wearing these units during training sessions and games may assist further studies in this area. In addition, as all conditioning workloads (i.e., cross-training and weight training) cannot be quantified through the use of GPS/accelerometers, combined research incorporating these objective measures with RPE-values and other data such as perceived muscle soreness, fatigue, mood, and sleep ratings (2,8,16) may provide additional insight into the training load–injury risk relationship of elite Australian football players. Having in-season fitness test data available may also provide useful information about the influence of higher (or lower) aerobic capacity and repeated sprint ability on subsequent injury incidence.

Across both seasonal phases, GPS/accelerometer-derived running load variables were shown to significantly relate to injury risk in elite Australian footballers. Overall, 3-weekly cumulative loads were found to have the strongest relationships with intrinsic injury incidence across both the preseason (3-weekly distance and 3-weekly sprint distance) and in-season (2-weekly distance and 3-weekly force load) phases. To reduce injury risk, the specific GPS/accelerometer variables identified in this study should be considered when monitoring and modifying player's weekly workload on an individual basis.

Practical Applications

With microtechnology (incorporating GPS and accelerometer measures) now appropriately validated for recording movement demands in athletes, derived running loads (particularly 2, 3, and 4-weekly cumulative loads) should be regularly monitored, as they may significantly relate to player injury risk. The specific loads identified in this study provide initial guidelines for the volumes that should be considered in Australian football for representing increases in injury risk. In a practical sense, load thresholds might then be determined for individual players, above which injury risk substantially increases. Medical and conditioning staff may then be able to make more objective and informed decisions on when player training or game loads should be modified or reduced, to limit their injury risk. However, applying these data to other AFL teams with different players and other team-sports should be performed carefully, as movement demands are specific to both player and sport.

Acknowledgments

No external financial support was received for this study.

References

1. Brewer, C, Dawson, B, Heasman, J, Stewart, G, and Cormack, S. Movement pattern comparisons in elite (AFL) and sub-elite (WAFL) Australian football games using GPS. *J Sci Med Sport* 13: 618–623, 2010.
2. Buchheit, M, Racinais, S, Bilsborough, JC, Bourdon, PC, Voss, SC, and Hocking, J. Monitoring fitness, fatigue and running performance during a pre-season training camp in elite football players. *J Sci Med Sport* 16: 550–555, 2013.
3. Burgess, D, Naughton, G, and Norton, K. Quantifying the gap between under 18 and senior AFL football: 2003 and 2009. *Int J Sports Physiol Perform* 7: 53–58, 2012.
4. Coutts, AJ and Duffield, R. Validity and reliability of GPS devices for measuring movement demands of team sports. *J Sci Med Sport* 13: 133–135, 2010.
5. Gabbe, BJ, Bennell, KL, Finch, CF, Wajswelner, H, and Orchard, JW. Predictors of hamstring injury at the elite level of Australian football. *Scand J Med Sci Sports* 16: 7–13, 2006.
6. Gabbett, TJ. The development and application of an injury prediction model for non-contact, soft-tissue injuries in elite collision sport athletes. *J Strength Cond Res* 24: 2593–2603, 2010.
7. Gabbett, TJ and Ullah, S. Relationship between running loads and soft-tissue injury in elite team sport athletes. *J Strength Cond Res* 26: 953–960, 2012.
8. Gastin, PB, Meyer, D, and Robinson, D. Perceptions of wellness to monitor adaptive responses to training and competition in elite Australian football. *J Strength Cond Res* 27: 2518–2526, 2013.
9. Gray, AJ and Jenkins, DG. Match analysis and the physiological demands of Australian football. *Sports Med* 40: 347–360, 2010.
10. Hiscock, D, Dawson, B, Heasman, J, and Peeling, P. Game movements and player performance in the Australian Football League. *Int J Perform Anal Sport* 12: 531–545, 2012.
11. Jennings, D, Cormack, S, Coutts, AJ, Boyd, LJ, and Aughey, RJ. Variability of GPS units for measuring distance in team sport movements. *Int J Sports Physiol Perform* 5: 565–569, 2010.
12. Johnston, R, Watsford, M, Pine, M, Spurrs, R, Murphy, A, and Pruyn, E. The validity and reliability of 5-Hz global positioning systems units to measure team sport movement demands. *J Strength Cond Res* 26: 758–765, 2012.
13. Knicker, AJ, Renshaw, I, Oldham, ARH, and Cairns, SP. Interactive processes link the multiple symptoms of fatigue in sport competition. *Sports Med* 41: 307–328, 2011.
14. Orchard, J and Seward, H. 20th Annual injury report: Season 2011. Available at: http://www.afl.com.au/injury%20report/tabid/13706/default.aspx. Accessed August 27, 2012.
15. Piggott, B, Newton, M, and McGuigan, M. The relationship between training load and injury and illness over a pre-season at an AFL Club. *J Aust Strength Cond* 17: 4–17, 2009.
16. Rogalski, B, Dawson, B, Heasman, J, and Gabbett, T. Training and game loads and injury risk in elite Australian footballers. *J Sci Med Sports* 16: 499–503, 2013.
17. Veale, JP, Pearce, AJ, Buttifant, D, and Carlson, JS. Anthropometric profiling of elite junior and senior Australian football players. *Int J Sports Physiol Perform* 5: 509–520, 2010.
18. Waldron, M, Worsfold, P, Twist, C, and Lamb, K. Concurrent validity and test-retest reliability of a global positioning system (GPS) and timing gates to assess sprint performance variables. *J Sports Sci* 29: 1613–1619, 2011.
19. Wisbey, B, Montgomery, PG, Pyne, DB, and Rattray, B. Quantifying movement demands of AFL football using GPS tracking. *J Sci Med Sport* 13: 531–536, 2010.