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# Running exposure is associated with the risk of hamstring strain injury in elite Australian footballers

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## ABSTRACT

**Background** To investigate the association between running exposure and the risk of hamstring strain injury (HSI) in elite Australian footballers.

**Methods** Elite Australian footballers (n=220) from 5 different teams participated. Global positioning system (GPS) data were provided for every athlete for each training session and match for the entire 2015 season. The occurrences of HSIs throughout the study period were reported. Receiver operator characteristic curve analyses were performed and the relative risk (RR) of subsequent HSI was calculated for absolute and relative running exposure variables related to distance covered above 10 and 24 km/hour in the preceding week/s.

**Results** 30 prospective HSIs occurred. For the absolute running exposure variables, weekly distance covered above 24 km/hour (>653 m, RR=3.4, 95% CI 1.6 to 7.2, sensitivity=0.52, specificity=0.76, area under the curve (AUC)=0.63) had the largest influence on the risk of HSI in the following week. For the relative running exposure variables, distance covered above 24 km/hour as a percentage of distance covered above 10 km/hour (>2.5%, RR=6.3, 95% CI 1.5 to 26.7, sensitivity=0.93, specificity=0.34, AUC=0.63) had the largest influence on the risk of HSI in the following week. Despite significant increases in the RR of HSI, the predictive capacity of these variables was limited.

**Conclusions** An association exists between absolute and relative running exposure variables and elite Australian footballers' risk of subsequent HSI, with the association strongest when examining data within 7–14 days. Despite this, the use of running exposure variables displayed limited clinical utility to predict HSI at the individual level.

## INTRODUCTION

Hamstring strain injuries (HSIs) are the most common injury in Australian football[1] and can result in reduced performance following return to play,[2] compromised neuromuscular function[3] and financial consequences for an athlete and their sporting organisation.[4] A number of non-modifiable risk factors for HSI have been previously investigated. These include increasing age,[5] previous HSI[5] and ethnicity.[6] Recently, however, focus has shifted to modifiable risk factors, which can be targeted through appropriate interventions to reduce the risk of injury.[7 8] Eccentric knee flexor weakness during the Nordic hamstring exercise,[7 8] short biceps femoris fascicle length[8] and muscle imbalances,[9 10] among others, are modifiable factors purported to increase the risk of HSI. However, despite significant scientific effort, the incidence of HSI in elite Australian football has not declined.[1] This suggests there remains much to be understood about the aetiology of HSI.

High-speed running is the most commonly cited mechanism of HSI.[11–14] It has been suggested that this is due to the hamstrings reaching peak lengths and levels of force and activation during the terminal swing phase of high-speed running, where they act to decelerate the flexing hip and rapidly extending knee.[13 14] Additionally, it has been suggested that the forceful eccentric contractions associated with high-speed running may lead to the accumulation of eccentrically induced muscle damage,[15] leaving the hamstrings more susceptible to strain injury.[16] Despite this hypothesis, only one study has examined the relationship between running exposure and the risk of subsequent HSI.[17] This work observed an increased risk of HSI in the subsequent week when an athlete's current weekly high-speed running distance exceeded their average weekly high-speed running distance (calculated across a 2-year period). This study, however, used data from a single team only, which limits the generalisability of these findings. Larger studies, using data from multiple teams, should enable a better understanding of the potential causal relationship between running exposure and subsequent HSI.

A greater appreciation for the properties of screening and/or monitoring tools, such as global positioning system (GPS) data, and their ability to predict athletes who go on to sustain an injury is also needed. The ideal risk factor should correctly identify all athletes who go on to be injured (sensitivity=1.0), and all athletes who do not (specificity=1.0). While a risk factor for HSI, such as running exposure,[17] will likely never achieve perfect properties for sensitivity (the ability to identify all athletes who go on to sustain a HSI) and specificity (the ability to identify all athletes who remain HSI free), receiver operator characteristic (ROC) curve analyses and the associated data, should help further the understanding of risk factor predictability.

Given high-speed running has been linked so closely to the aetiology and risk of HSI,[12–14 17] the purpose of the current study was to investigate the association between running exposure and the risk of HSI in elite Australian footballers, across multiple teams. Furthermore, this study will also highlight the test properties of running exposure variables when trying to predict the occurrence of HSI in the subsequent week.

## METHODS

### Study design

This prospective cohort study was conducted during the 2015 Australian Football League (AFL)

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season. The study period started at the beginning of preseason (November 2014) and concluded following the end of the home and away season (September 2015). Prior to the initiation of the study, demographic and lower limb injury history data for each athlete were provided to the research team by the medical staff of each team. During the study, all athletes wore GPS units during field training sessions and matches to monitor running speeds and distances. Throughout the study period, any prospectively occurring HSIs were reported to the research team. This study was approved by the Queensland University of Technology and Australian Catholic University Human Research Ethics Committees.

### Participants

Six teams (out of 18, 33% of the total competition) competing in the AFL were approached and agreed to participate in the study. Each athlete was provided with a plain language statement outlining the study and provided informed written consent. One team did not provide prospective HSI data despite repeated efforts from the investigators. As a result, 5 teams and 220 elite Australian footballers were included in the analyses.

### Demographic and lower limb injury history data

Demographic data for each athlete were provided to the research team, which included age (years), stature (cm), mass (kg), playing position and years of playing experience in the AFL. The medical staff for each of the participating teams also completed a questionnaire detailing the lower limb injury history of each athlete prior to the initiation of the study. This included history of HSI within the preceding 12 months and history of ACL injury at any stage during the athlete's career.

### Reporting of prospective HSI

For the purposes of this investigation, a prospectively occurring HSI was defined as acute pain in the posterior thigh that resulted in disruption of the hamstring fibres, as confirmed by MRI.[7] All teams reported that MRI was performed when medical staff suspected a HSI. For all injuries that fulfilled these criteria, the relevant team doctor or physiotherapist completed a standard injury report form, which detailed the limb that sustained the injury, the hamstring muscle that was injured, the location of the injury (ie, proximal muscle–tendon junction, mid muscle belly, etc), mechanism of injury (high-speed running, jumping, etc), severity of injury determined from clinical examination and/or MRI grading and the number of days taken to return to full training.

### GPS data collection

All athletes wore OptimEye S5 GPS athlete monitoring systems (10 Hz, Catapult Sports, Melbourne, Australia) during field training sessions and matches. The aforementioned GPS units have been shown to have high interunit reliability (interclass correlation=0.89) when measuring high-speed running distances.[18] Despite the high interunit reliability, participating teams made every effort to ensure athletes wore the same unit for each training session and match. At the beginning of each training session or match, the GPS units were fitted into a specially designed pocket on the back between the scapulae, by each individual team's high performance staff.[19]

### Data analysis

Each GPS data file (which corresponded to an athlete's individual training session or match) was imported into and analysed using the standard manufacturer software (Catapult Sprint V.5.1.7, Catapult Sports, Melbourne, Australia). For each file, distance covered above 10 and 24 km/hour, in metres, was determined using a dwell time of 1 s. Data from the two speed bands were then summed across a week for each individual athlete, where a week was defined as a 7-day period starting on Monday and concluding on Sunday. Once the data were condensed into weekly totals, five absolute variables and three relative variables were calculated for distance covered in the two speed bands.

Absolute variables:

- Weekly distance (m)—the total distance covered across a single week.
- Two-weekly distance (m)—the accumulation of distance covered across a rolling 2-week period.
- Three-weekly distance (m)—the accumulation of distance covered across a rolling 3-week period.
- Four-weekly distance (m)—the accumulation of distance covered across a rolling 4-week period.
- Absolute week-to-week change in distance (m)—the change in distance covered from one week compared with the previous week. A positive value indicates an increase from one week to the next, whereas a negative value indicates a decrease from one week to the next.

Relative variables:

- Acute:chronic workload ratio—the ratio of distance covered in a week (acute workload) compared with the weekly average of the same variable over the preceding 4-week period (chronic workload). Note that the 4-week period over which the chronic workload is calculated is inclusive of the acute workload week.[20]
- Relative week-to-week change in distance—the ratio of distance covered in a week compared with the previous week. A value >1 indicates an increase from one week to the next, whereas a value <1 indicates a decrease from one week to the next.
- Distance covered above 24 km/hour as a percentage of distance covered above 10 km/hour—weekly distance covered above 24 km/hour expressed as a percentage of weekly distance covered above 10 km/hour.

While previous investigations[19 21] have reported total distance (ie, distance covered above 0 km/hour), as well as reporting distance covered relative to time (ie, m/min), this was not possible in the current study. The data files were provided to the research team in a raw format without activity periods defined. Consequently, low speed movements (<10 km/hour) could not be solely attributed to athlete movement. In the event an athlete did not register any distance covered above 10 km/hour during a week, or in situations where training or match GPS data were not available (playing in a roofed stadium, technical faults, etc), these data (370 athlete exposure weeks) and subsequently impacted data were censored from statistical analysis. When an athlete sustained a HSI, the week during which the injury occurred was identified. As an injury typically resulted in the cessation of all on-field activity, the week prior to the injury occurring was considered the athlete's last full week and was the index week for statistical analysis. All other data for the athletes that sustained a prospective HSI were censored from analyses.

### Statistical analyses

All statistical analyses were performed using JMP V.10.02 (SAS Institute, Cary, North Carolina, USA). The mean and SD of age, stature, mass and years of playing experience were determined. Weekly distance covered above 10 and 24 km/hour were determined to be non-normally distributed, assessed using the

Kolmogorov-Smirnov test. As a result, the median and IQR is reported for these data. The relative risk (RR) and associated 95% CIs of sustaining a HSI was determined for athletes with or without prior HSI and athletes with or without prior ACL injury. The RR of injury was also determined for athletes above age cut-points that represent the 25th, 50th and 75th percentiles in this cohort.

ROC curve analyses were performed and sensitivity, specificity and area under the curve (AUC) for absolute and relative variables were determined. For the absolute variables, the RR of sustaining a HSI in the subsequent week and the associated 95% CIs was determined by comparing the rate of HSI in athletes above and below the cut-point which maximised sensitivity and specificity, as determined from the ROC curve analyses. For the relative variables, the RR of sustaining a HSI in the subsequent week and the associated 95% CIs was determined by comparing the rate of HSI in athletes above and below several arbitrary cut-points determined by the investigators. A RR was deemed statistically significant if the 95% CIs did not cross 1.0.

**Table 1** The percentage rate of HSI based on absolute running exposure variables and cut-points representing the 25th, 50th and 75th percentiles, using data from 220 elite Australian footballers

| Running exposure variable and associated cut-point | Number of data points < the cut-point | % of HSI < the cut-point | Number of data points ≥ the cut-point | % of HSI ≥ the cut-point |
|---|---|---|---|---|
| Weekly distance covered | | | | |
| Above 10 km/hour | | | | |
| 7976 m | 1630 | 0.31 | 4895 | 0.45 |
| 11 680 m | 3262 | 0.31 | 3263 | 0.52 |
| 15 367 m | 4892 | 0.35 | 1633 | 0.61 |
| Above 24 km/hour | | | | |
| 182 m | 1629 | 0.31 | 4896 | 0.45 |
| 372 m | 3258 | 0.28 | 3267 | 0.55 |
| 639 m | 4893 | 0.27 | 1632 | 0.86 |
| Two-weekly distance covered | | | | |
| Above 10 km/hour | | | | |
| 16 167 m | 1520 | 0.39 | 4562 | 0.44 |
| 22 652 m | 3039 | 0.49 | 3043 | 0.36 |
| 29 123 m | 4561 | 0.46 | 1521 | 0.33 |
| Above 24 km/hour | | | | |
| 413 m | 1516 | 0.20 | 4566 | 0.50 |
| 758 m | 3036 | 0.40 | 3046 | 0.46 |
| 1238 m | 4561 | 0.37 | 1521 | 0.59 |
| Three-weekly distance covered | | | | |
| Above 10 km/hour | | | | |
| 23 912 m | 1419 | 0.35 | 4258 | 0.49 |
| 33 056 m | 2838 | 0.46 | 2839 | 0.46 |
| 42 603 m | 4257 | 0.47 | 1420 | 0.42 |
| Above 24 km/hour | | | | |
| 637 m | 1419 | 0.63 | 4258 | 0.52 |
| 1123 m | 2838 | 0.35 | 2839 | 0.56 |
| 1808 m | 4255 | 0.40 | 1422 | 0.63 |
| Four-weekly distance covered | | | | |
| Above 10 km/hour | | | | |
| 32 344 m | 1317 | 0.61 | 3952 | 0.40 |
| 43 430 m | 2634 | 0.42 | 2635 | 0.49 |
| 55 433 m | 3951 | 0.48 | 1318 | 0.38 |
| Above 24 km/hour | | | | |
| 871 m | 1316 | 0.23 | 3953 | 0.53 |
| 1503 m | 2633 | 0.34 | 2636 | 0.57 |
| 2382 m | 3951 | 0.38 | 1318 | 0.68 |
| Absolute week-to-week change in distance covered | | | | |
| Above 10 km/hour | | | | |
| −3259 m | 1520 | 0.33 | 4562 | 0.46 |
| 676 m | 3040 | 0.30 | 3042 | 0.56 |
| 5074 m | 4561 | 0.33 | 1521 | 0.72 |
| Above 24 km/hour | | | | |
| −175 m | 1517 | 0.33 | 4565 | 0.46 |
| 13 m | 3038 | 0.36 | 3044 | 0.49 |
| 229 m | 4558 | 0.29 | 1524 | 0.85 |

HSI, hamstring strain injury.

## RESULTS

### Power calculations

Using G*Power (V.3.1.7), power was calculated as 0.98 for the use of two-tailed independent t-tests to compare groups post hoc (input parameters: effect size=0.80, α=0.05, sample size group 1=190, sample size group 2=30). An effect size of 0.80 was selected as this indicates a large effect.[22]

### Cohort details

In total, 8349 athlete exposure weeks were collated from 220 athletes (age 23.4±3.5 years; stature 188.0±7.5 cm; mass 87.2 ±8.5 kg; years of playing experience 4.7±3.5 years). Of these, 29 athletes had sustained a HSI in the 12 months preceding the study period. During the preseason period, the average number of field training sessions per week, where GPS data were collected, was 3.2±1.0. During the in-season period this number dropped to 2.3±0.5 sessions per week and the average number of matches per week was 1.0±0.3. Only in one instance did two participating teams play two matches in the same week (where a week was defined as a 7-day period starting on Monday and concluding on Sunday). During the study period, the median weekly distance covered by each athlete was 11 680 m above 10 km/hour (IQR=7391 m) and 372 m above 24 km/hour (IQR=457 m).

**Table 2** The percentage rate of HSI based on relative running exposure variables and arbitrary cut-points, using data from 220 elite Australian footballers

| Running exposure variable and associated cut-point | Number of data points < the cut-point | % of HSI < the cut-point | Number of data points ≥ the cut-point | % of HSI ≥ the cut-point |
|---|---|---|---|---|
| *Acute:chronic workload for distance covered* | | | | |
| Above 10 km/hour | | | | |
| 0.50 | 483 | 0.41 | 4786 | 0.46 |
| 0.75 | 1064 | 0.38 | 4205 | 0.48 |
| 1.00 | 2384 | 0.42 | 2885 | 0.49 |
| 1.25 | 3763 | 0.43 | 1506 | 0.53 |
| 1.50 | 4530 | 0.42 | 739 | 0.68 |
| 1.75 | 4878 | 0.43 | 391 | 0.77 |
| 2.00 | 5004 | 0.46 | 265 | 0.38 |
| Above 24 km/hour | | | | |
| 0.50 | 877 | 0.23 | 4345 | 0.51 |
| 0.75 | 1639 | 0.49 | 3583 | 0.45 |
| 1.00 | 2596 | 0.39 | 2626 | 0.53 |
| 1.25 | 3531 | 0.42 | 1691 | 0.53 |
| 1.50 | 4182 | 0.45 | 1040 | 0.48 |
| 1.75 | 4539 | 0.46 | 683 | 0.44 |
| 2.00 | 4763 | 0.48 | 459 | 0.22 |
| *Relative week-to-week change in distance covered* | | | | |
| Above 10 km/hour | | | | |
| 0.50 | 664 | 0.45 | 4932 | 0.45 |
| 0.75 | 1472 | 0.27 | 4124 | 0.51 |
| 1.00 | 2715 | 0.33 | 2881 | 0.56 |
| 1.25 | 3771 | 0.29 | 1825 | 0.77 |
| 1.50 | 4315 | 0.35 | 1281 | 0.78 |
| 1.75 | 4659 | 0.39 | 937 | 0.75 |
| 2.00 | 4879 | 0.37 | 717 | 0.98 |
| Above 24 km/hour | | | | |
| 0.50 | 1182 | 0.17 | 4223 | 0.54 |
| 0.75 | 1986 | 0.30 | 3419 | 0.56 |
| 1.00 | 2766 | 0.36 | 2639 | 0.57 |
| 1.25 | 3383 | 0.33 | 2022 | 0.69 |
| 1.50 | 3793 | 0.32 | 1612 | 0.81 |
| 1.75 | 4087 | 0.32 | 1318 | 0.91 |
| 2.00 | 4310 | 0.30 | 1095 | 1.10 |
| *Distance covered above 24 km/hour as a percentage of distance covered above 10 km/hour* | | | | |
| 2.5% | 2194 | 0.09 | 4327 | 0.58 |
| 5% | 4914 | 0.33 | 1607 | 0.68 |
| 7.5% | 6013 | 0.42 | 508 | 0.39 |
| 10% | 6366 | 0.42 | 155 | 0.00 |

Acute:chronic workload ratio is the ratio of distance covered in a week (acute workload) compared with the weekly average of the same variable over the preceding 4-week period (chronic workload). Note that the 4-week period over which the chronic workload is calculated is inclusive of the acute workload week. Relative week-to-week change in distance is the ratio of distance covered in a week compared with the previous week. A value >1 indicates an increase from one week to the next, whereas a value <1 indicates a decrease from one week to the next.
HSI, hamstring strain injury.

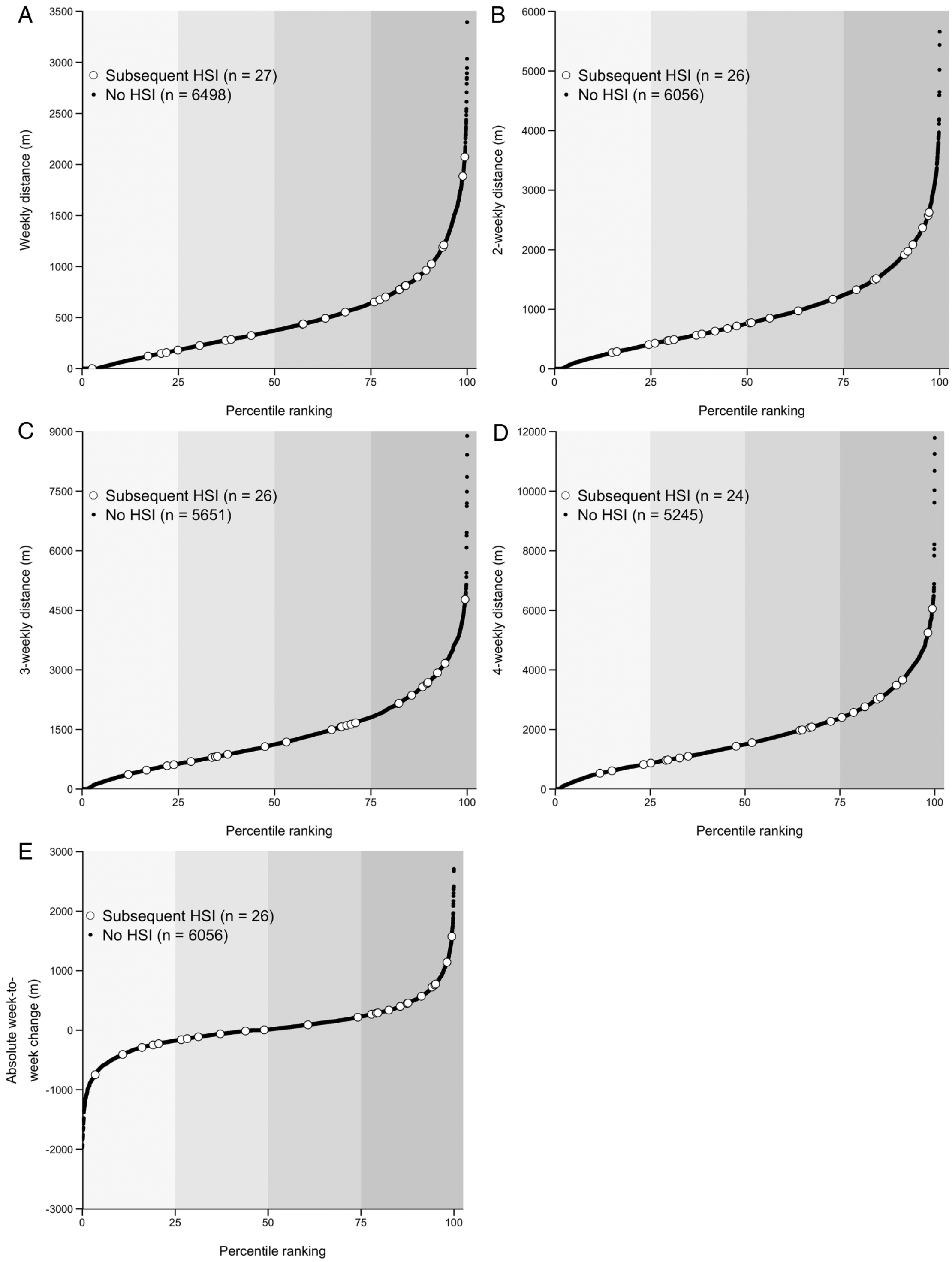


**Figure 1** Distribution of data for absolute running exposure variables above 24 km/hour. Exposures that resulted in a HSI in the following week are signified by the open circles. HSI, hamstring strain injury.

### Prospective injury details

On average, one HSI occurred every 2623 and 103 km ran by the cohort above 10 and 24 km/hour, respectively. Thirty athletes sustained a prospective HSI (age 24.6±3.3 years; stature 186.8 ±5.7 cm; mass 86.3±6.5 kg; years of playing experience 5.2±3.8), while the remaining 190 did not (age 24.2±3.6 years; stature 188.3±7.8 cm; mass 87.4±8.8 kg; years of playing experience 4.6 ±3.5). Of the 30 prospectively occurring HSIs (15 on the dominant limb, 15 on the non-dominant limb), 28 of the injuries were located in the biceps femoris, with two injuries occurring in the semimembranosus. High-speed running was the primary mechanism of injury (53%). A total of 13 injuries occurred during the pre-season period, with 17 injuries occurring during the in-season period. The distribution of playing positions in the subsequently injured group was as follows: back 34%; forward 13%; midfield 50%; ruck 3%. This suggests that midfielders were over-represented in the subsequently injured group as opposed to the uninjured group (back 26%; forward 29%; midfield 38%; ruck 7%).

The percentage rates of HSI above and below cut-points that represent the 25th, 50th and 75th percentiles for the absolute

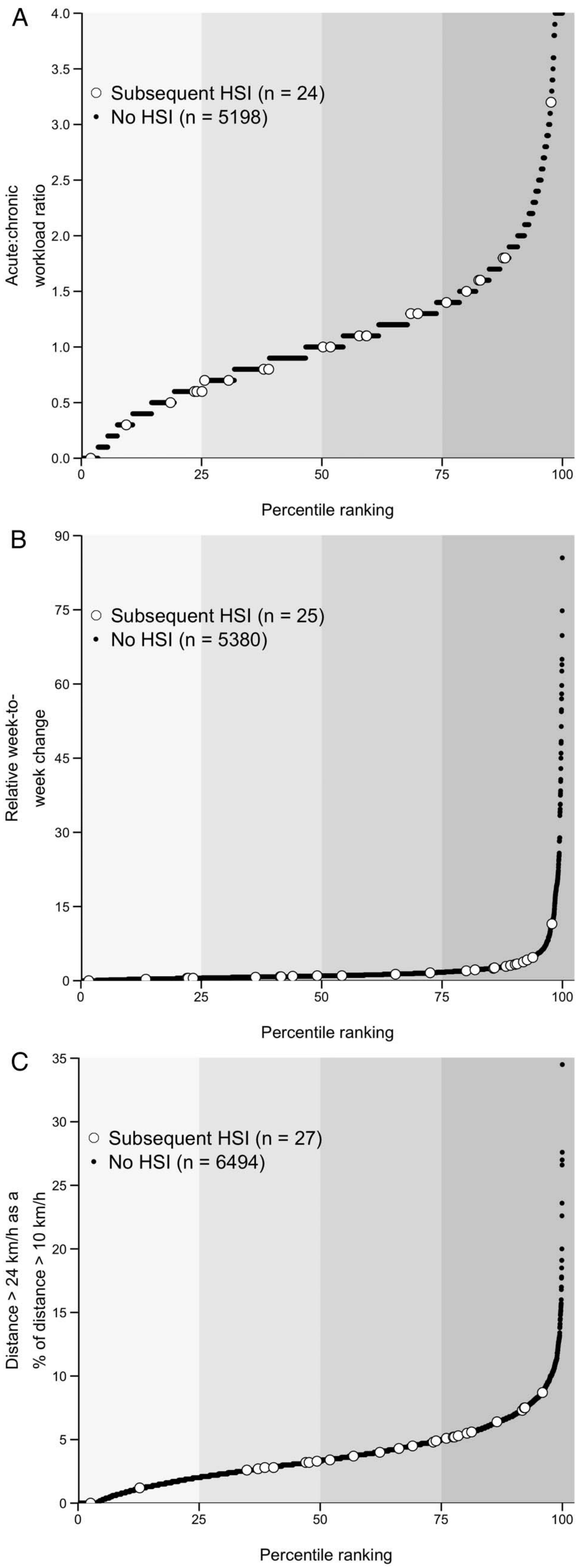


**Figure 2** Distribution of data for relative running exposure variables above 24 km/hour. Exposures that resulted in a HSI in the following week are signified by the open circles. Acute:chronic workload ratio is the ratio of distance covered in a week (acute workload) compared with the weekly average of the same variable over the preceding 4-week period (chronic workload). Note that the 4-week period over which the chronic workload is calculated is inclusive of the acute workload week. Relative week-to-week change in distance is the ratio of distance covered in a week compared with the previous week. A value >1 indicates an increase from one week to the next, whereas a value <1 indicates a decrease from one week to the next. HSI, hamstring strain injury.

running exposure variables can be found in table 1. The percentage rates of HSI above and below arbitrary cut-points for the relative running exposure variables can be found in table 2. The distribution of data and the incidence, or lack thereof, of HSI in the subsequent week for absolute and relative running exposure variables above 24 km/hour can be found in figures 1 and 2, respectively.

## RR and risk factor predictive properties

Athletes with a previous HSI (within the 12 months preceding the study period) did not have a statistically significant increased risk of prospective HSI when compared with those without a previous HSI (RR=2.0, 95% CI 0.9 to 4.2). Similarly, athletes with an ACL injury at any point during their career did not have an increased risk of prospective HSI compared with those with no history of ACL injury (RR=0.9, 95% CI 0.2 to 3.3). When compared with athletes <22 years old, athletes ≥22 (RR=1.3, 95% CI 0.6 to 3.1), ≥25 (RR=1.4, 95% CI 0.6 to 3.3) or ≥28 (RR=1.1, 95% CI 0.4 to 3.2) years old were not at an increased risk of prospective HSI.

For the absolute running exposure variables, the RR of sustaining a HSI in the subsequent week, using cut-points derived from ROC curve analyses, ranged from 1.5 to 3.9 and AUC values ranged from 0.50 to 0.63 (table 3). Weekly distance covered above 24 km/hour (>653 m, RR=3.4, 95% CI 1.6 to 7.2, sensitivity=0.52, specificity=0.76, AUC=0.63) and absolute week-to-week change in distance covered above 24 km/hour (>218 m, RR=3.3, 95% CI 1.5 to 7.2, sensitivity=0.54, specificity=0.74, AUC=0.61) had the largest significant influence on the risk of HSI in the subsequent week (table 3). None of the absolute running exposure variables had both a sensitivity and specificity value above 0.60 (table 3).

For the relative running exposure variables, the RR of sustaining a HSI in the subsequent week, using arbitrarily selected cut-points, ranged from 0.5 to 3.6 and AUC values ranged from 0.52 to 0.63 (table 4). Relative week-to-week change in distance covered above 24 km/hour (>2.00, RR=3.6, 95% CI 1.7 to 7.9, sensitivity=0.48, specificity=0.80, AUC=0.62) and distance covered above 24 km/hour as a percentage of distance covered above 10 km/hour (>2.5%, RR=6.3, 95% CI 1.5 to 26.7, sensitivity=0.93, specificity=0.34, AUC=0.63) had the largest significant influence on the risk of HSI in the subsequent week (table 4). Similar to the absolute variables, none of the relative running exposure variables had both a sensitivity and specificity value above 0.60 (table 4).

## DISCUSSION

The purpose of the current study was to investigate the association between running exposure and the risk of HSI in elite Australian footballers across multiple teams. The key finding of this study was that while significant RR for sustaining a HSI in the subsequent week were identified using both absolute and relative measures of running exposure, the accompanying sensitivity and specificity values for these variables were limited. The data indicate that an association likely exists between running exposure and risk of subsequent HSI in elite Australian footballers; however, the metrics examined in the current study do not

**Table 3** RR of Australian footballers sustaining a HSI in the following week using absolute running exposure variables and receiver operator characteristic curve-derived cut-points and associated values of predictive properties

| Running exposure variable and associated cut-point | RR (95% CI) | Sensitivity | Specificity | AUC |
|---|---|---|---|---|
| *Weekly distance covered* | | | | |
| Above 10 km/hour | | | | |
| 13 312 m | 2.4 (1.1 to 5.3) | 0.59 | 0.63 | 0.58 |
| Above 24 km/hour | | | | |
| 653 m | 3.4 (1.6 to 7.2) | 0.52 | 0.76 | 0.63 |
| *Two-weekly distance covered* | | | | |
| Above 10 km/hour | | | | |
| 27 785 m | 1.5 (0.7 to 3.4) | 0.38 | 0.71 | 0.50 |
| Above 24 km/hour | | | | |
| 406 m | 3.9 (0.9 to 16.3) | 0.92 | 0.24 | 0.57 |
| *Three-weekly distance covered* | | | | |
| Above 10 km/hour | | | | |
| 32 006 m | 1.6 (0.7 to 3.7) | 0.65 | 0.46 | 0.51 |
| Above 24 km/hour | | | | |
| 1495 m | 2.5 (1.2 to 5.5) | 0.58 | 0.65 | 0.60 |
| *Four-weekly distance covered* | | | | |
| Above 10 km/hour | | | | |
| 45 600 m | 1.4 (0.6 to 3.2) | 0.54 | 0.55 | 0.50 |
| Above 24 km/hour | | | | |
| 1972 m | 2.5 (1.1 to 5.7) | 0.58 | 0.65 | 0.59 |
| *Absolute week-to-week change in distance covered* | | | | |
| Above 10 km/hour | | | | |
| 2524 m | 2.2 (1.0 to 4.8) | 0.58 | 0.62 | 0.60 |
| Above 24 km/hour | | | | |
| 218 m | 3.3 (1.5 to 7.2) | 0.54 | 0.74 | 0.61 |

AUC, area under the curve; HSI, hamstring strain injury; RR, relative risk.

provide useful information as to identifying the individuals who go on to sustain a HSI.

The evidence presented in the current study provides objective data for practitioners working in elite Australian football who are responsible for monitoring running exposure as part of larger HSI risk mitigation strategies. The cut-points provided for RR determination, while holding some relevance for monitoring strategies, should be viewed in light of the accompanying sensitivity and specificity values (tables 3 and 4). Screening tests are often used to detect signs of disease in individuals and reduce mortality rates through early intervention.[23] In this instance, the outcome is dichotomous, and the individual is either classified as having the disease or not. The objective in elite sport is often to mitigate the risk of future injury, but this is always balanced against the need to maximise performance.[20] In such environments, screening and/or serial monitoring of presumed risk factors is implemented in an attempt to determine athletes that are low risk or high risk and to instigate interventions to mitigate risk according to the variable/s of interest.[23] Considerable overlap in running exposure data was observed between the injured and uninjured weekly athlete exposures, as illustrated in figures 1 and 2. Therefore, although some of these variables demonstrated significant RR, their clinical utility is likely limited. A worked example calculating the pre-test and post-test probabilities for weekly distance covered above 24 km/hour can be found in figure 3. The pre-test and post-test probabilities are the probabilities of sustaining a subsequent HSI before and after being classified above a predetermined cut-point. In the worked example (figure 3), the pretest probability for sustaining a HSI is 0.4%. After being classified above 653 m for weekly distance covered above 24 km/hour, the post-test probability increased to 0.9% (figure 3). This means that being classified above 653 m only accounts for a 0.5% increase in the probability of sustaining a HSI in the subsequent week. Such a small increase in probability highlights the limited 'predictive' capacity of these variables in an applied setting.

Accounting for the aforementioned limitations regarding RR and the disassociation with predictive ability, the risk of sustaining a HSI in the subsequent week was greatest (RR=6.3) when the distance covered above 24 km/hour was >2.5% of distance covered above 10 km/hour. For example, if an athlete ran 10 000 m above 10 km/hour in a week, and more than 250 m of this was above 24 km/hour, the risk of HSI in the following week was 6.3 times higher compared with weekly exposures where there was <250 m ran above 24 km/hour. It should be noted, however, that while this cut-point correctly identified 93% (sensitivity=0.93) of those who went on to sustain a HSI, specificity was only 0.34. Despite a different definition of high-speed running (above 18 km/hour used by Windt *et al*[24]), previous work somewhat corroborates the use of such a marker, as it identified an increased risk of all injury types if the percentage of total distance covered above 18 km/hour was >3.7%.

When weekly distance covered above 24 km/hour was >653 m and absolute week-to-week change in distance covered above 24 km/hour was >218 m, there was a significant increase in the risk of HSI in the subsequent week (3.4-fold and 3.3-fold, with AUC values of 0.63 and 0.61, respectively). Previous work observed an increased risk of HSI in the subsequent week (OR=6.4, 95% CI 3.0 to 14.4) in elite Australian footballers, when weekly distance covered above 24 km/hour was higher than the individual athlete's average weekly high-speed running distance across 2 years.[17] Interestingly, in prior

**Table 4** RR of Australian footballers sustaining a HSI in the following week using relative running exposure variables and arbitrary cut-points and associated receiver operator characteristic curve values of predictive properties

| Running exposure variable and associated cut-point | RR (95% CI) | Sensitivity | Specificity | AUC |
|---|---|---|---|---|
| *Acute:chronic workload for distance covered* | | | | |
| Above 10 km/hour | | | | 0.55 |
| 0.5 | 1.1 (0.3 to 4.7) | 0.92 | 0.09 | |
| 0.75 | 1.3 (0.4 to 3.7) | 0.83 | 0.20 | |
| 1 | 1.1 (0.5 to 2.6) | 0.58 | 0.45 | |
| 1.25 | 1.2 (0.5 to 2.9) | 0.33 | 0.71 | |
| 1.5 | 1.6 (0.6 to 4.3) | 0.21 | 0.86 | |
| 1.75 | 1.8 (0.5 to 5.9) | 0.13 | 0.93 | |
| 2 | 0.8 (0.1 to 6.1) | 0.04 | 0.95 | |
| Above 24 km/hour | | | | 0.52 |
| 0.5 | 2.2 (0.5 to 9.4) | 0.92 | 0.17 | |
| 0.75 | 0.9 (0.4 to 2.1) | 0.67 | 0.31 | |
| 1 | 1.4 (0.6 to 3.1) | 0.58 | 0.50 | |
| 1.25 | 1.3 (0.5 to 2.9) | 0.38 | 0.68 | |
| 1.5 | 1.1 (0.4 to 2.8) | 0.21 | 0.80 | |
| 1.75 | 0.9 (0.3 to 3.2) | 0.13 | 0.87 | |
| 2 | 0.5 (0.1 to 3.3) | 0.04 | 0.91 | |
| *Relative week-to-week change in distance covered* | | | | |
| Above 10 km/hour | | | | 0.61 |
| 0.5 | 1.0 (0.3 to 3.3) | 0.88 | 0.12 | |
| 0.75 | 1.9 (0.6 to 5.5) | 0.84 | 0.26 | |
| 1 | 1.7 (0.7 to 3.8) | 0.64 | 0.49 | |
| 1.25 | 2.6 (1.2 to 5.8) | 0.56 | 0.67 | |
| 1.5 | 2.2 (1.0 to 5.0) | 0.40 | 0.77 | |
| 1.75 | 1.9 (0.8 to 4.6) | 0.28 | 0.83 | |
| 2 | 2.6 (1.1 to 6.3) | 0.28 | 0.87 | |
| Above 24 km/hour | | | | 0.62 |
| 0.5 | 3.2 (0.8 to 13.6) | 0.92 | 0.22 | |
| 0.75 | 1.8 (0.7 to 4.6) | 0.76 | 0.37 | |
| 1 | 1.6 (0.7 to 3.5) | 0.60 | 0.51 | |
| 1.25 | 2.1 (1.0 to 4.7) | 0.56 | 0.63 | |
| 1.5 | 2.5 (1.2 to 5.6) | 0.52 | 0.70 | |
| 1.75 | 2.9 (1.3 to 6.3) | 0.48 | 0.76 | |
| 2 | 3.6 (1.7 to 7.9) | 0.48 | 0.80 | |
| *Distance covered above 24 km/hour as a percentage of distance covered above 10 km/hour* | | | | 0.63 |
| 2.5% | 6.3 (1.5 to 26.7) | 0.93 | 0.34 | |
| 5% | 2.1 (1.0 to 4.5) | 0.41 | 0.75 | |
| 7.5% | 0.9 (0.2 to 4.0) | 0.07 | 0.92 | |
| 10% | NA | 0.00 | 0.98 | |

Acute:chronic workload ratio is the ratio of distance covered in a week (acute workload) compared with the weekly average of the same variable over the preceding 4-week period (chronic workload). Note that the 4-week period over which the chronic workload is calculated is inclusive of the acute workload week. Relative week-to-week change in distance is the ratio of distance covered in a week compared with the previous week. A value >1 indicates an increase from one week to the next, whereas a value <1 indicates a decrease from one week to the next.
AUC, area under the curve; HSI, hamstring strain injury; RR, relative risk.

work, the OR diminished as the analysis window increased to take into account running exposure across the previous 2, 3 and 4 weeks, respectively.[17] The findings from the current study and prior work[17] tend to suggest that the association between running exposure and risk of HSI is strongest when examining distance covered above 24 km/hour within a 7–14-day window. For example, the current work found no association between the acute:chronic workload ratio and subsequent HSI with the acute window set at one week and the chronic window set at four weeks. A chronic window of a different timeframe (ie, 3–6 weeks) may have produced different results however.

HSIs are often considered acute and traumatic in nature;[25] however, this and earlier work[17] suggest that there is some association between running exposure in the prior 7–14 days and the likelihood of HSI. It is very likely that different tissues (muscle, tendon, ligament and bone) or pathologies may have varying critical time windows, as has been reported previously in cricket.[26] Specifically for the hamstrings, it has been suggested that greater exposure to high-speed running and the associated forceful eccentric contractions required during the terminal swing phase[13] could lead to the accumulation of eccentrically induced muscle damage.[15] This damage may then leave the hamstrings more susceptible to macroscopic trauma, such as a strain injury.[25] This hypothesis is yet to be validated, however the time course of eccentrically induced muscle damage[15] and the presumed increased risk of macroscopic trauma following this[16] fits somewhat with the notion that prior running exposure may influence susceptibility of HSI for some time after.

Pre-test probability = (true positives + false negatives) / total sample

Pre-test probability = (14 + 13) / 6561

Pre-test probability = 0.004

Pre-test odds = pre-test probability / (1 - pre-test probability)

Pre-test odds = 0.004 / (1 – 0.004)

Pre-test odds = 0.004

Positive likelihood ratio = sensitivity / (1 – specificity)

Positive likelihood ratio = 0.52 / (1 – 0.76)

Positive likelihood ratio = 2.17

Post-test odds = pre-test odds × positive likelihood ratio

Post-test odds = 0.004 × 2.17

Post-test odds = 0.009

Post-test probability = post-test odds / (post-test odds + 1)

Post-test probability = 0.009 / (0.009 + 1)

Post-test probability = 0.009

**Figure 3** A worked example calculating the pretest and post-test probabilities of sustaining a subsequent HSI before and after being classified above 653 m for weekly distance covered above 24 km/hour. HSI, hamstring strain injury.

Certainly, other variables are likely to contribute to an increased susceptibility of HSI (ie, eccentric strength, susceptibility to eccentrically induced muscle damage and 'fatigability')[25] and such interactions would need to be examined in larger investigations of longer durations.

There may be additional benefit in expressing speed bands as a percentage of an individual athlete's maximum speed (ie, distance covered and efforts performed above 75% of maximum speed)[19] or to normalise running exposure to individualised historical data.[17] However, given five separate teams participated in this study, individualised approaches such as these were not possible. This limitation should be viewed in light of the benefit of using a larger sample size, which is integral when exploring associations between risk factors (ie, running exposure) and the incidence of HSI.[27] It is also important to consider that other variables, some known and perhaps some unknown, contribute to an athlete's risk of sustaining a HSI. As with all injuries, the aetiology of HSI is multifaceted[25 28] and factors such as an athlete's age, injury history, ethnicity, muscle architecture and level of eccentric hamstring strength are all likely to interact with running exposure variables to ultimately determine an athlete's susceptibility of HSI. Susceptible athletes also need to be exposed to an inciting event[27] (ie, high-speed running, jumping to mark a ball or being forced into hip flexion during a tackle) and this introduces another degree of unpredictability. While the investigators anticipated sufficient statistical power to perform multivariate analysis, using weekly athlete exposures as the unit for analysis precluded this approach. Future work should aim to explore the interaction between age, HSI history and eccentric strength (just to name a few) with running exposure variables to better understand how multiple factors impact on individual athletes' risk profiles for future HSI. In light of the current work, strong consideration should be given to using the athlete as the unit of measurement where appropriate, as opposed to weekly athlete exposures. Given the aforementioned limitations, future work of a similar nature should also explore the application of alternate and more divergent statistical methodologies. Statistical learning techniques, such as neural networks and agent-based models, have been used to improve the ability to predict complex outcomes such as economic and meteorological patterns.[29 30] The application of such techniques in the sports injury prediction is yet to be explored however.

There are additional limitations in the current study. First, each participating team provided the research team with GPS data files in a raw format without defined activity periods (such as when specific training drills were performed). Because of this, the investigators were unable to determine when, following the activation of the GPS units, athletes were fitted with the device. As a result of this, total distance was excluded as a variable of interest. It remains unknown whether the addition of total distance would introduce meaningful information beyond the data presented. Second, while all teams reported that all GPS data files collected were provided to the research team, some teams acknowledged that GPS data were not collected for some sessions, such as low-intensity recovery sessions. There is the possibility that running during these low-intensity sessions may contribute to the association with HSI; however, the current study could not include these data in the analysis. Furthermore, data from the recovery sessions that were provided by some teams indicated that running speeds rarely exceeded 10 km/hour. It was also not possible to monitor the running distances of athletes outside the confines of their teams. The possibility, however unlikely, that athletes completed running or training sessions without the knowledge of their teams was not controlled for in the current study. Finally, the current findings only relate to HSIs that fulfil the criteria of acute pain in the posterior thigh that resulted in disruption of the hamstring fibres, as confirmed by MRI. It was not possible to align different teams' criteria for a 'functional' HSI (MRI negative, but clinically positive)[31] and it is difficult to determine how the inclusion of these injuries would have impacted the findings.

In conclusion, there is an association between absolute and relative running exposure variables and risk of subsequent HSI in elite Australian footballers, with the association strongest when examining data within a 7–14-day window. Despite this, the use of running exposure variables on their own displayed limited practical utility, as expressed through measures of sensitivity and specificity and the associated calculations of pretest and post-test probabilities. While difficult to achieve, ongoing efforts to study multiple variables measured on a serial basis, which have relevance to HSI, are needed to determine what combination of measures, if any, can improve the identification of athletes who go on to sustain a HSI.

### What are the findings?

- There is an association between running exposure and the risk of hamstring strain injury (HSI) in elite Australian footballers.
- The risk of HSI was greatest when examining the 7–14 days prior to injury.
- The independent use of running exposure variables to identify athletes who went on to sustain a HSI displayed limited clinical utility.
- Ongoing efforts to study multiple variables and their predictive properties are needed to determine what combination, if any, can improve the identification of athletes who go on to sustain a HSI.

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**Patient consent** Obtained.

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# Running exposure is associated with the risk of hamstring strain injury in elite Australian footballers

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