Abstract

Background: Hamstring strain injuries (HSI) are common within the Australian Football League (AFL) with most occurring during high-speed running (HSR). Therefore, this study investigated possible relationships between mean session running distances, session ratings of perceived exertion (s-RPE) and HSIs in AFL footballers. **Methods:** Global positioning systems (GPS) derived running distances and s-RPE for all matches and training sessions over two AFL seasons were obtained from one AFL team. All HSIs were documented and each player's running distances and s-RPE were standardised to their 2-yearly session average, then compared between injured and uninjured players in the four weeks (week -1, -2, -3, -4) preceding each injury. **Results:** Higher than 'typical' (i.e., Z = 0) HSR session means were associated with a greater likelihood of HSI (week -1 OR = 6.44, 95%CI = 2.99 to 14.41; p<0.001; summed weeks -1 and -2 OR = 3.06, 95%CI = 2.03 – 4.75, p<0.001; summed weeks -1, -2 and -3 OR = 2.22, 95%CI = 1.66 – 3.04, p<0.001; and summed weeks -1, -2, -3 and -4 OR = 1.96, 95%CI = 1.54 - 2.51, p<0.001). However, trivial differences were observed between injured and uninjured groups for standardised s-RPE, total distance travelled and distances covered whilst accelerating and decelerating. With increasing AFL experience there was a decrease in injury risk (OR = 0.77; 95%CI = 0.57 – 0.97; p=0.02). Furthermore, modelling of HSR data indicated that reducing mean distances in the week prior to injury may decrease the probability of HSI. **Conclusion:** Exposing players to transient increases in HSR distances above their 2-yearly session average increased the odds of HSI. However, reducing HSR in the week prior to hamstring strain injury may offset HSI risk. Future work should investigate the proposed model's efficacy in HSI reduction.

What are the new findings?

- Exposure to transiently elevated high-speed running volumes, relative to those an athlete is regularly performing, increases the probability of hamstring injury.
- Absolute high-speed running distances were not associated with hamstring injury risk.
- Greater AFL playing experience was associated with lower risk of hamstring injury

How might it impact on clinical practice in the near future

- This model suggests the need to monitor changes in each player's high-speed running session distances.
- The results highlight the importance of avoiding large and rapid increases in high-speed running -volumes.
- Reducing the volume of high speed running every four weeks may reduce risk of hamstring injury.

Introduction

Australian Rules football (ARF) is a challenging contact sport requiring high levels of fitness and skill. Within Australia, the elite level of ARF is the Australian Football League (AFL). Each AFL season spans November to September, during which teams complete a preseason (preparation) phase followed by 22 weekly games, and possibly finals. In the last two decades, hamstring strain injuries have remained an ongoing problematic issue, constituting a large proportion of soft tissue injuries sustained in the AFL.[1] The predominant injury mechanism for hamstring strain injuries is sprinting,[2] and fatigue may play a role because higher injury rates have been reported during the latter stages of soccer and rugby matches.[3 4]

On average, an AFL game lasts 100:01 ± 14:22 min during which players cover a distance of 12.2 ±1.9 km, reach maximum velocities of 30.1 ± 6.7 km h^{-1} and perform numerous accelerations (246 ± 47 (>4 kmh^{-1} in 1 s)) and decelerations (14 ± 5 (over 10 km h^{-1} in 1 s)).[5] Unsurprisingly, teams within the AFL implement rigorous monitoring systems to carefully observe training and competition loads,[6-8] allowing for appropriate programming to ensure optimal performance [9] and a reduced injury risk.[6] Two popular monitoring methods include 1) objective running loads collected via global positioning system (GPS) devices,[5] and 2) subjective ratings of perceived exertion (s-RPE), which together allow for the quantification of physiological stress caused by the application of external loads (e.g. running loads) [10] and the estimation of injury risk.[6]

Previous studies have found that rapid increases in training and game loads increase the risk of injuries in AFL footballers, [6] elite cricketers [11] and rugby league players.[11] Furthermore, GPS derived data from elite rugby league demonstrates that greater volumes of high-speed running result in more soft-tissue injuries.[12] Additionally, regular interchanges made during

AFL matches have been suggested to protect players against hamstring strain injuries but increase the risk for opposition players.[13]

The predominant injury mechanism for hamstring strain injuries is high-speed running ,[2] however, no studies have explored the effect of high-speed running distances on the risk of hamstring injury. Therefore, the aim of this study was to determine whether running distances and s-RPE were associated with an increased risk of hamstring strain injury in elite AFL players. We hypothesised that rapid and large increases in high-speed running distances over four weeks might influence hamstring strain injury risk.

Materials and Methods

Study Design

This study employed an observational prospective cohort design and was completed over 102 weeks spanning the 2013 and 2014 AFL and the concurrent ‘reserves’ competition (North East Australian Football League) seasons (Nov 2012 – Aug 2013 and Nov 2013 – Aug 2014). All participants had their running distances collected via GPS devices (V4 Catapult, South Melbourne, Australia) and s-RPE collected via SMARTABASE (Fusion sport, Brisbane, Australia).

Participants

Fifty-one elite male footballers (age = 22.2 ± 3.4 y, height = 188.2 ± 7.1 cm, mass = 86.6 ± 8.7 kg with a median of 4 y (range 1-12 y) of AFL playing experience from a single AFL team were recruited for this study. The university’s human research ethics committee approved the study and participants gave informed written consent.

GPS and s-RPE Data Collection

GPS measures of athlete movements have previously been reported to be reasonably accurate and reliable.[14 15] Each player was fitted with a 10 Hz GPS unit (V4 Catapult, South Melbourne, Australia) contained within their guernsey or undergarment on the upper back during all running sessions and games throughout the two season observational period. Uploaded data containing ‘signal drop-out’ errors or players not involved in the football drills were removed.

SMARTABASE (Fusion Sport, Brisbane, Australia) is a software platform that allows players to enter their subjective judgments of training session or match load (a product of rating of perceived exertion and duration (min)). This measurement is used in the attempt to assess how the athletes are coping with training loads and previous work has demonstrated moderate to very large associations between s-RPE and both high-speed running ($r = 0.51$) and total distance covered ($r = 0.88$).[10] Players were required to report RPE’s within 5 hours of training sessions and 4-6 hours of matches.

Hamstring Strain Injury

A hamstring strain injury was defined as acute pain in the posterior thigh that caused immediate cessation of exercise.[2] Damage to the muscle and or tendon was later confirmed by the club’s physiotherapist via clinical assessment or magnetic resonance imaging examination. All reports were forwarded to the investigators at the conclusion of the competitive season.

Data Analysis

Once GPS and s-RPE data were entered in a spreadsheet, all match and training sessions were analysed (number of files = 11457; median, minimum and maximum files collected per player = 246, 79 and 302, respectively). Playing experience was defined as the time spent within the AFL system and was included to assess its effect on hamstring strain injury risk. The derived variables included: the session ratings of perceived exertion, total distance travelled (km), high-speed running distance ($\geq$24 km h^{-1}) and distance (m) covered whilst accelerating (>3m/s/s) and decelerating (<-3m/s/s). For each variable, players had their weekly session totals summed across the two years. A two-yearly session mean and the session mean for each of the four weeks (week -1, week -2, week -3 and week -4) leading up to each injury was also calculated. The four weeks preceding each injury was chosen for three reasons: (1) hamstring strain injuries occurred randomly throughout the season without any apparent relationship to absolute running distance, (2) four weeks is generally accepted as an appropriate mesocycle length,[16] and (3) previous findings have used this time period to estimate injury risk.[12 17] To standardise the variables for each player, high-speed running distances were log transformed and z-scores calculated using the following formula:

$$z = (VAR_{WSM} – VAR_{2YSM})/ VAR_{2YSSD}$$

where VAR_{WSM} is a variable’s weekly session mean, for each of the four weeks preceding each hamstring strain injury, and VAR_{2YSM} and VAR_{2YSSD} represent the variable’s session mean and standard deviation across the two years, respectively. Standardised scores of zero then represented a ‘typical’ week for a particular player while positive and negative scores indicated heavier or lighter than typical training loads respectively. Injured players were those who sustained a hamstring strain injury at any stage in the two years including the pre-season training and in-season periods. No players had a current hamstring strain injury at the start of data collection (November 2012).

Statistical Analysis

All statistical analyses were performed using JMP 10.02 (SAS Institute, Inc., Cary, NC).

Independent *t*-tests were used to compare total high-speed running distance performed in each season between injured (INJ) and uninjured (UNINJ) groups. Paired *t*-tests were used to compare the high-speed running distances between the first and second season.

Variables for which the 95% confidence intervals (CI) fell below zero in any of the four week 'blocks' prior to injury were removed from further analysis (Figure 1). Standardised mean high-speed running session distance was the only variable for which the 95%CI remained above zero (Figure 1). Independent sample *t*-tests were used to compare four-week mean high-speed running distances between injured and uninjured players in each of the four-week blocks prior to every hamstring strain injury. Once it was established that the injured group were performing greater standardised mean high-speed running session distances, two models were produced to assess the likelihood of hamstring strain injury. The first model examined week -1, the sum of weeks -1 and -2, the sum of weeks -1, -2 and -3, and the sum of weeks -1, -2, -3 and -4. The second model examined the association between mean high-speed running session distances observed in week -1 and the sum of weeks -2, -3 and -4- prior to injury. Age has previously been reported to be a risk factor for hamstring strain injury.[2 18] Therefore, we assessed whether a relationship between playing experience and injury existed. This variable was added to both models. Z scores were reported as means with 95% confidence intervals.

At each injury time-point, Z-scores for the preceding four weeks were calculated for all players and independent sample *t*-tests used to compare mean session distances between injured and uninjured players. Logistic regression was employed to determine the odds ratio (OR) of injury with increasing or decreasing standardised mean high-speed running session distances, in the four weeks leading up to injury (Figure 2). Additionally, the effect of standardised mean high-speed running session distance changes in the week prior to injury on hamstring strain injury risk were modelled (Figure 3). Two injuries were excluded from analysis due to missing GPS data. Statistical significance was set at $P<0.05$.

RESULTS

Hamstring strain injury **incidence and distances covered**

Twenty-two hamstring strain injuries were sustained across the 2013 (n=11) and 2014 (n=11) seasons, all of which occurred after the first 13-weeks of each preseason. Two injuries were excluded from analysis due to incomplete data. As previously reported,[19] the majority of hamstring strain injuries were sustained during match-play (14 out of 20) rather than training. On average, players covered a total distance of 807 ± 95 km in the 2013 season and 775.3 ± 166 km in the 2014 season, of which 22.6 ± 8 km and 15.5 ± 5 km were at high-speed (>24km h^{-1}). No significant differences were found in total absolute high-speed running distances between the injured and uninjured groups in 2013 (INJ mean = 22.1 ± 5 km; 95% CI = 16 – 28 km; range 18 – 30 km; and UNINJ mean = 22.6 ± 9 km; 95% CI = 20 – 25 km; range = 2 – 46 km; p = 0.90) or 2014 (INJ mean = 16.6 ± 4 km; 95% CI = 14 – 19 km; range = 13 – 23 km; and UNINJ mean = 15.2 ± 6 km; 95% CI = 13 – 17 km; range = 2 – 30 km; p=0.49). Furthermore, despite a significant reduction in the absolute distance of high-speed running between the two seasons (p<0.01), there was no decrease in injury rates. Players with greater than four years playing experience did not sustain hamstring injury: INJ (median = 4, range = 1 – 4 y) compared to UNINJ (median = 4, range = 1 – 12 y).

Relationships between running distances and hamstring strain injuries

Due to the 95% CIs falling below "0" in both the INJ and UNINJ in the four weeks leading up to injury, session ratings of perceived exertion, total distance covered, acceleration and deceleration distances (Figure 1) were excluded from further analysis. However, standardised high-speed running distances were higher in the INJ than the UNINJ (Figure 1).

INSERT FIGURE 1 HERE

The average summed four week standardised high-speed running distances for INJ and UNINJ were; $z = 2.36 \pm 2.76$ and $z = -0.05 \pm 1.63$, respectively ($p<0.001$). Using logistic regression, the likelihood of hamstring strain injuries increased (OR = 1.96, 95%CI = 1.54 - 2.51, $p<0.001$) with greater relative high-speed running distances in the four weeks prior to injury (Figure 2). The largest effect of high-speed running distance on injury risk was observed in the week prior to injury (OR = 6.44, 95%CI = 2.99 to 14.41; $p<0.001$) followed by the sum of weeks -1 and -2 (OR = 3.06, 95%CI = 2.03 – 4.75, $p<0.001$) and the sum of weeks -1, -2, and -3 (OR = 2.22, 95%CI = 1.66 – 3.04, $p<0.001$). When added to the model, greater playing experience was associated with a reduced likelihood of injury risk (OR = 0.77, 95%CI = 0.57 – 0.97, $p=0.021$) without confounding the effect of standardised high-speed running distance (OR = 1.91, 95%CI = 1.51 – 2.47, $p=0.022$; $p<0.001$).

INSERT FIGURE 2 HERE

Figure 3 shows the impact of the final week of the four-week mesocycle on the probability of hamstring strain injury. Here the association between the summed high-speed running session distances in weeks -4, -3 and -2 (OR = 1.73, 95% CI = 1.24 - 2.39, $p = 0.001$) and the week preceding injury (OR = 3.02, 95% CI = 1.36 - 7.26, $p = 0.006$) was tested and the resultant probability of hamstring strain injury determined. According to this model, the probability of hamstring strain injuries was decreased with reduced standardised high-speed running distances in week -1. When experience was added to this model, a similar protective effect was observed (OR = 0.78, 95% CI = 0.57 – 0.96, p = 0.022) and there was no evidence to suggest it confounded the other variables (summed high-speed running session distances in weeks -4, -3 and -2 OR = 1.70, 95% CI = 1.22 - 2.36, p = 0.002, and the week preceding injury OR = 2.98, 95% CI = 1.33 - 7.27, p = 0.007).

INSERT FIGURE 3 HERE

DISCUSSION

This study is the first to investigate relationships between athlete running distances and hamstring strain injuries. Players who performed significantly more than their two-yearly average amount of high-speed running (>24 km h^{-1}) in the four-weeks prior to injury had a greater risk of hamstring strain injury than players who did not. In contrast, hamstring strain injury risk was not influenced by the player's s-RPE, total distance covered, absolute amount of high-speed running or by the total distances covered while accelerating or decelerating. Acute high-speed running loads during -1 week had a greater impact on injury risk compared to chronic loads (the sum of -2, -3 and -4). These findings demonstrate that transiently elevated high-speed running distances increase the likelihood of hamstring strain injury. A secondary finding was that an increase in playing experience resulted in a small protective benefit against hamstring strain injury.

Previous studies have reported relationships between high transient training loads and all forms of injury.[6 12 20] The results from this study add to the training-injury literature [6 9 17 21-25] by reaffirming the injury risk associated with high-speed running.[12] The current model has been based on performance [9] and injury risk models.[17] These models are based on the premise that training load has both positive and negative influences, with higher chronic loads (i.e. 4-weeks) associated with better fitness [9] and higher acute (i.e. 1-week) loads associated with a greater risk of injury.[17] Moreover, previous investigations suggest that fitness levels increase when chronic load exceeds acute load [9] and injury risk increases when acute load outweighs chronic load.[11 17] Our major finding was similar to these previous observations, whereby players exposed to large and rapid increases in high-speed running distances above their 2-yearly average were more likely to sustain a hamstring strain injury than players who were not. However, it was beyond the scope of this descriptive study to determine the optimal time period to estimate future risk of hamstring injury.

From a training-performance perspective, careful consideration should be taken when interpreting and applying the current findings to the high performance sports setting. In alignment with earlier reports showing a positive relationship between greater training distance [26] and intensity [27] with improved performance, Gabbett and Ullah [12] suggest a fine balance exists between training load restriction, to prevent injury, and increasing training loads to physically prepare players for competition. Therefore, taking into account the need for an appropriate stimulus to improve performance, we used the current data to produce a model, based on a common mesocycle period of four weeks.[16] Our model suggests that players will be exposed to greater risk of hamstring strain injury when high-speed running distances extend beyond a player's typical load either acutely or chronically. Planned decreased mean high-speed running session distances in the fourth week of each mesocycle may offer the 'balance' between injury prevention and performance.[12] As such, the execution of three weeks of relatively high mean high-speed running session distance followed by a recovery week, where less distance is covered, may allow the application of overload while also reducing the risk of hamstring strain injury. Therefore, the current findings provide some support for monitoring player's high-speed running and the periodization of training load as a means of reducing hamstring strain injury risk while maintaining a desired chronic load for performance.[28-30] It is noteworthy to consider that , whilst the current model(s) suggest particular time periods can estimate hamstring strain injury risk, other soft-tissue injuries may be susceptible to different loading cycles, occurring more rapidly or slowly in response to changes in training volume.

Finally, there is evidence to support the association between advanced age and hamstring strain injury in some [2 18] but not all studies.[31] A survey from the football departments of AFL clubs has revealed a belief amongst some conditioning staff, that younger and older players have an elevated risk of hamstring strain injury. The rationale behind this belief was that younger players were unable to tolerate training loads and older players are unable to sufficiently recover between training sessions and matches.[32] Interestingly, the current findings show a small protective benefit against hamstring strain injury with increasing playing experience. However, when interpreting these findings it is important to consider the fact that the sample only included one AFL team and the practices performed by this club may vary significantly from other clubs. While purely speculative, it may be that more experienced players are more robust having survived the early years of an AFL career, and can manage themselves and their workloads better or are monitored more closely than less experienced teammates.

In summary, this study highlighted the influence high-speed running distances performed over four weeks has on hamstring strain injury risk in elite AFL players. These results demonstrated the increasing likelihood of injury when athletes performed more high-speed running than that to which they were accustomed across a four-week period. Therefore, gradual increases in each individual's standardised mean high-speed running session distance should be prescribed over a period of time, thereby ensuring players have required fitness levels for competition with a reduced risk of injury. Future work exploring the impact of periodic reductions in mean high-speed running session distance on hamstring strain injury risk is warranted.

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Contributorship statement

SD was the principle investigator and was involved with study design, recruitment, analysis and manuscript preparation. CF was involved with data collection and analysis. AS, DO, and MW were involved with the study design, analysis and manuscript preparation. TG was involved with analysis and manuscript preparation. All authors had full access to all of the data (including statistical reports and tables) in the study and can take responsibility for the integrity of the data and the accuracy of the data analysis.

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Figure legends

Figure 1 – Standardised weekly session loads (y-axis) for each of the four weeks prior to each injury (x-axis) are shown from top to bottom: deceleration, acceleration, total distance covered, session ratings of perceived exertion and high-speed running. Dashed and solid lines represent injured and uninjured groups, respectively. Errors bars represent 95% CI.

Figure 2 – The influence of summed four-week standardised mean high-speed running session distances on the probability of hamstring strain injury. Average high-speed running mean session distance corresponds to zero on the x-axis.

Figure 3 Modeling of the impact of standardised mean high-speed running session distances in the four weeks prior to hamstring injury. Injury risk is influenced by mean high-speed running session distances in weeks -4 to -2 (as shown on the x axis) and in week -1 (as shown by the curves). The probability of hamstring strain injuries can be influenced by relative high-speed running volumes in weeks -2 to -4 (x-axis) and/or week -1 prior to injury. The 2-yearly average high-speed running session distance is represented by 0 on the x-axis. Each curve represents the standardised mean high-speed running session distance covered in the first week (week -1) prior to injury; top curve = high to very-high (0.94 – 1.82), second curve = moderate to high (0.08 – 0.94), third curve = low to moderate (-0.82 – 0.08), fourth curve = very low to low (-1.71 – -0.82) and bottom curve = extremely low to very-low (-2.62 – -1.71), z-score thresholds within brackets.