

32 **Abstract**

33 **Background:** Hamstring strain injuries (HSI) are common within the Australian Football
34 League (AFL) with most occurring during high-speed running (HSR). Therefore, this study
35 investigated possible relationships between mean session running distances, session ratings of
36 perceived exertion (s-RPE) and HSIs in AFL footballers. **Methods:** Global positioning systems
37 (GPS) derived running distances and s-RPE for all matches and training sessions over two AFL
38 seasons were obtained from one AFL team. All HSIs were documented and each player's
39 running distances and s-RPE were standardised to their 2-yearly session average, then compared
40 between injured and uninjured players in the four weeks (week -1, -2, -3, -4) preceding each
41 injury. **Results:** Higher than 'typical' (i.e., $Z = 0$) HSR session means were associated with a
42 greater likelihood of HSI (week -1 OR = 6.44, 95%CI = 2.99 to 14.41; $p < 0.001$; summed weeks
43 -1 and -2 OR = 3.06, 95%CI = 2.03 – 4.75, $p < 0.001$; summed weeks -1, -2 and -3 OR = 2.22,
44 95%CI = 1.66 – 3.04, $p < 0.001$; and summed weeks -1, -2, -3 and -4 OR = 1.96, 95%CI = 1.54 -
45 2.51, $p < 0.001$). However, trivial differences were observed between injured and uninjured
46 groups for standardised s-RPE, total distance travelled and distances covered whilst accelerating
47 and decelerating. With increasing AFL experience there was a decrease in injury risk (OR =
48 0.77; 95%CI = 0.57 – 0.97; $p = 0.02$). Furthermore, modelling of HSR data indicated that
49 reducing mean distances in the week prior to injury may decrease the probability of HSI.
50 **Conclusion:** Exposing players to transient increases in HSR distances above their 2-yearly
51 session average increased the odds of HSI. However, reducing HSR in the week prior to
52 hamstring strain injury may offset HSI risk. Future work should investigate the proposed
53 model's efficacy in HSI reduction.

54 **What are the new findings?**

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

59

60 **How might it impact on clinical practice in the near future**

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

67

68 **Introduction**

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

77 On average, an AFL game lasts $100:01 \pm 14:22$ min during which players cover a distance of
78 12.2 ± 1.9 km, reach maximum velocities of 30.1 ± 6.7 km h⁻¹ and perform numerous
79 accelerations (246 ± 47 (>4 kmh⁻¹ in 1 s)) and decelerations (14 ± 5 (over 10 km h⁻¹ in 1 s)).[5]
80 Unsurprisingly, teams within the AFL implement rigorous monitoring systems to carefully
81 observe training and competition loads,[6-8] allowing for appropriate programming to ensure
82 optimal performance [9] and a reduced injury risk.[6] Two popular monitoring methods include
83 1) objective running loads collected via global positioning system (GPS) devices,[5] and 2)
84 subjective ratings of perceived exertion (s-RPE), which together allow for the quantification of
85 physiological stress caused by the application of external loads (e.g. running loads) [10] and the
86 estimation of injury risk.[6]

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

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

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

99 **Materials and Methods**

100 **Study Design**

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

107 **Participants**

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

112 **GPS and s-RPE Data Collection**

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

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

125 **Hamstring Strain Injury**

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

130 **Data Analysis**

131 Once GPS and s-RPE data were entered in a spreadsheet, all match and training sessions were
132 analysed (number of files = 11457; median, minimum and maximum files collected per player =
133 246, 79 and 302, respectively). Playing experience was defined as the time spent within the AFL

134 system and was included to assess its effect on hamstring strain injury risk. The derived
135 variables included: the session ratings of perceived exertion, total distance travelled (km), high-
136 speed running distance ($\geq 24 \text{ km h}^{-1}$) and distance (m) covered whilst accelerating ($> 3 \text{ m/s}^2$) and
137 decelerating ($< -3 \text{ m/s}^2$). For each variable, players had their weekly session totals summed across
138 the two years. A two-yearly session mean and the session mean for each of the four weeks (week
139 -1, week -2, week -3 and week -4) leading up to each injury was also calculated. The four weeks
140 preceding each injury was chosen for three reasons: (1) hamstring strain injuries occurred
141 randomly throughout the season without any apparent relationship to absolute running distance,
142 (2) four weeks is generally accepted as an appropriate mesocycle length,[16] and (3) previous
143 findings have used this time period to estimate injury risk.[12 17] To standardise the variables
144 for each player, high-speed running distances were log transformed and z-scores calculated using
145 the following formula:

$$146 \quad z = (\text{VAR}_{WSM} - \text{VAR}_{2YSM}) / \text{VAR}_{2YSSD}$$

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

155

156 **Statistical Analysis**

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

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

161 Variables for which the 95% confidence intervals (CI) fell below zero in any of the four week
162 ‘blocks’ prior to injury were removed from further analysis (Figure 1). Standardised mean high-
163 speed running session distance was the only variable for which the 95%CI remained above zero
164 (Figure 1). Independent sample *t*-tests were used to compare four-week mean high-speed running
165 distances between injured and uninjured players in each of the four-week blocks prior to every
166 hamstring strain injury. Once it was established that the injured group were performing greater
167 standardised mean high-speed running session distances, two models were produced to assess the
168 likelihood of hamstring strain injury. The first model examined week -1, the sum of weeks -1 and
169 -2, the sum of weeks -1, -2 and -3, and the sum of weeks -1, -2, -3 and -4. The second model
170 examined the association between mean high-speed running session distances observed in week -
171 1 and the sum of weeks -2, -3 and -4- prior to injury. Age has previously been reported to be a
172 risk factor for hamstring strain injury.[2 18] Therefore, we assessed whether a relationship
173 between playing experience and injury existed. This variable was added to both models. Z scores
174 were reported as means with 95% confidence intervals.

175 At each injury time-point, Z-scores for the preceding four weeks were calculated for all players
176 and independent sample *t*-tests used to compare mean session distances between injured and
177 uninjured players. Logistic regression was employed to determine the odds ratio (OR) of injury
178 with increasing or decreasing standardised mean high-speed running session distances, in the
179 four weeks leading up to injury (Figure 2). Additionally, the effect of standardised mean high-

180 speed running session distance changes in the week prior to injury on hamstring strain injury risk
181 were modelled (Figure 3). Two injuries were excluded from analysis due to missing GPS data.
182 Statistical significance was set at $P < 0.05$.

183

184 **RESULTS**

185 Hamstring strain injury **incidence and distances covered**

186 Twenty-two hamstring strain injuries were sustained across the 2013 ($n=11$) and 2014 ($n=11$)
187 seasons, all of which occurred after the first 13-weeks of each preseason. Two injuries were
188 excluded from analysis due to incomplete data. As previously reported,[19] the majority of
189 hamstring strain injuries were sustained during match-play (14 out of 20) rather than training. On
190 average, players covered a total distance of 807 ± 95 km in the 2013 season and 775.3 ± 166 km
191 in the 2014 season, of which 22.6 ± 8 km and 15.5 ± 5 km were at high-speed ($>24\text{km h}^{-1}$). No
192 significant differences were found in total absolute high-speed running distances between the
193 injured and uninjured groups in 2013 (INJ mean = 22.1 ± 5 km; 95% CI = 16 – 28 km; range 18
194 – 30 km; and UNINJ mean = 22.6 ± 9 km; 95% CI = 20 – 25 km; range = 2 – 46 km; $p = 0.90$) or
195 2014 (INJ mean = 16.6 ± 4 km; 95% CI = 14 – 19 km; range = 13 – 23 km; and UNINJ mean =
196 15.2 ± 6 km; 95% CI = 13 – 17 km; range = 2 – 30 km; $p=0.49$). Furthermore, despite a
197 significant reduction in the absolute distance of high-speed running between the two seasons
198 ($p < 0.01$), there was no decrease in injury rates. Players with greater than four years playing
199 experience did not sustain hamstring injury: INJ (median = 4, range = 1 – 4 y) compared to
200 UNINJ (median = 4, range = 1 – 12 y).

201 **Relationships between running distances and hamstring strain injuries**

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

206 INSERT FIGURE 1 HERE

207 The average summed four week standardised high-speed running distances for INJ and UNINJ
208 were; $z = 2.36 \pm 2.76$ and $z = -0.05 \pm 1.63$, respectively ($p < 0.001$). Using logistic regression, the
209 likelihood of hamstring strain injuries increased (OR = 1.96, 95%CI = 1.54 - 2.51, $p < 0.001$) with
210 greater relative high-speed running distances in the four weeks prior to injury (Figure 2). The
211 largest effect of high-speed running distance on injury risk was observed in the week prior to
212 injury (OR = 6.44, 95%CI = 2.99 to 14.41; $p < 0.001$) followed by the sum of weeks -1 and -2
213 (OR = 3.06, 95%CI = 2.03 – 4.75, $p < 0.001$) and the sum of weeks -1, -2, and -3 (OR = 2.22,
214 95%CI = 1.66 – 3.04, $p < 0.001$). When added to the model, greater playing experience was
215 associated with a reduced likelihood of injury risk (OR = 0.77, 95%CI = 0.57 – 0.97, $p = 0.021$)
216 without confounding the effect of standardised high-speed running distance (OR = 1.91, 95%CI
217 = 1.51 – 2.47, $p = 0.022$; $p < 0.001$).

218 INSERT FIGURE 2 HERE

219 Figure 3 shows the impact of the final week of the four-week mesocycle on the probability of
220 hamstring strain injury. Here the association between the summed high-speed running session
221 distances in weeks -4, -3 and -2 (OR = 1.73, 95% CI = 1.24 - 2.39, $p = 0.001$) and the week
222 preceding injury (OR = 3.02, 95% CI = 1.36 - 7.26, $p = 0.006$) was tested and the resultant
223 probability of hamstring strain injury determined. According to this model, the probability of

224 hamstring strain injuries was decreased with reduced standardised high-speed running distances
225 in week -1. When experience was added to this model, a similar protective effect was observed
226 (OR = 0.78, 95% CI = 0.57 – 0.96, p = 0.022) and there was no evidence to suggest it
227 confounded the other variables (summed high-speed running session distances in weeks -4, -3
228 and -2 OR = 1.70, 95% CI = 1.22 - 2.36, p = 0.002, and the week preceding injury OR = 2.98,
229 95% CI = 1.33 - 7.27, p = 0.007).

230 INSERT FIGURE 3 HERE

231 **DISCUSSION**

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

243 Previous studies have reported relationships between high transient training loads and all forms
244 of injury.[6 12 20] The results from this study add to the training-injury literature [6 9 17 21-25]
245 by reaffirming the injury risk associated with high-speed running.[12] The current model has

246 been based on performance [9] and injury risk models.[17] These models are based on the
247 premise that training load has both positive and negative influences, with higher chronic loads
248 (i.e. 4-weeks) associated with better fitness [9] and higher acute (i.e. 1-week) loads associated
249 with a greater risk of injury.[17] Moreover, previous investigations suggest that fitness levels
250 increase when chronic load exceeds acute load [9] and injury risk increases when acute load
251 outweighs chronic load.[11 17] Our major finding was similar to these previous observations,
252 whereby players exposed to large and rapid increases in high-speed running distances above their
253 2-yearly average were more likely to sustain a hamstring strain injury than players who were not.
254 However, it was beyond the scope of this descriptive study to determine the optimal time period
255 to estimate future risk of hamstring injury.

256 From a training-performance perspective, careful consideration should be taken when
257 interpreting and applying the current findings to the high performance sports setting. In
258 alignment with earlier reports showing a positive relationship between greater training distance
259 [26] and intensity [27] with improved performance, Gabbett and Ullah [12] suggest a fine
260 balance exists between training load restriction, to prevent injury, and increasing training loads
261 to physically prepare players for competition. Therefore, taking into account the need for an
262 appropriate stimulus to improve performance, we used the current data to produce a model,
263 based on a common mesocycle period of four weeks.[16] Our model suggests that players will be
264 exposed to greater risk of hamstring strain injury when high-speed running distances extend
265 beyond a player's typical load either acutely or chronically. Planned decreased mean high-speed
266 running session distances in the fourth week of each mesocycle may offer the 'balance' between
267 injury prevention and performance.[12] As such, the execution of three weeks of relatively high
268 mean high-speed running session distance followed by a recovery week, where less distance is

269 covered, may allow the application of overload while also reducing the risk of hamstring strain
270 injury. Therefore, the current findings provide some support for monitoring player's high-speed
271 running and the periodization of training load as a means of reducing hamstring strain injury risk
272 while maintaining a desired chronic load for performance.[28-30] It is noteworthy to consider
273 that , whilst the current model(s) suggest particular time periods can estimate hamstring strain
274 injury risk, other soft-tissue injuries may be susceptible to different loading cycles, occurring
275 more rapidly or slowly in response to changes in training volume.

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

288 In summary, this study highlighted the influence high-speed running distances performed over
289 four weeks has on hamstring strain injury risk in elite AFL players. These results demonstrated
290 the increasing likelihood of injury when athletes performed more high-speed running than that to
291 which they were accustomed across a four-week period. Therefore, gradual increases in each

292 individual's standardised mean high-speed running session distance should be prescribed over a
293 period of time, thereby ensuring players have required fitness levels for competition with a
294 reduced risk of injury. Future work exploring the impact of periodic reductions in mean high-
295 speed running session distance on hamstring strain injury risk is warranted.

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298 **Contributorship statement**

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

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394

395 **Figure legends**

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

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

403 Figure 3 Modeling of the impact of standardised mean **high-speed running** session distances in
404 the four weeks prior to hamstring injury. Injury risk is influenced by mean **high-speed running**
405 session distances in weeks -4 to -2 (as shown on the x axis) and in week -1 (as shown by the
406 curves). The probability of **hamstring strain injuries** can be influenced by relative **high-speed**
407 **running** volumes in weeks -2 to -4 (x-axis) and/or week -1 prior to injury. The 2-yearly average
408 **high-speed running** session distance is represented by 0 on the x-axis. Each curve represents the
409 standardised mean **high-speed running** session distance covered in the first week (week -1) prior
410 to injury; top curve = high to very-high (0.94 – 1.82), second curve = moderate to high (0.08 –
411 0.94), third curve = low to moderate (-0.82 – 0.08), fourth curve = very low to low (-1.71 – -
412 0.82) and bottom curve = extremely low to very-low (-2.62 – -1.71), z-score thresholds within
413 brackets.