

1 **TITLE**

2 **Eccentric Knee-flexor Strength and Risk of Hamstring Injuries in Rugby Union: A**
3 **Prospective Study**

4
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26 **Running Title**

27 Eccentric hamstring strength and injury risk

28

29 **ABSTRACT**

30 **BACKGROUND:** Hamstring strain injuries (HSIs) represent the most common cause of lost
31 playing time in rugby union. Eccentric knee-flexor weakness and between-limb imbalance in
32 eccentric knee-flexor strength are associated with a heightened risk of hamstring injury in
33 other sports; however these variables have not been explored in rugby union. **PURPOSE:** To
34 determine if lower levels of eccentric knee-flexor strength or greater between-limb imbalance
35 in this parameter during the Nordic hamstring exercise are risk-factors for hamstring strain
36 injury in rugby union. **STUDY DESIGN:** Cohort study; level of evidence, 3. **METHODS:**
37 This prospective study was conducted over the 2014 Super Rugby and Queensland Rugby
38 Union seasons. In total, 178 rugby union players (age, 22.6 ± 3.8 years; height, 185 ± 6.8 cm;
39 mass, 96.5 ± 13.1 kg) had their eccentric knee-flexor strength assessed using a custom-made
40 device during the pre-season. Reports of previous hamstring, quadriceps, groin, calf and
41 anterior cruciate ligament injury were also obtained. The main outcome measure was
42 prospective occurrence of hamstring strain injury. **RESULTS:** Twenty players suffered at
43 least one hamstring strain during the study period. Players with a history of hamstring strain
44 injury had 4.1 fold (RR = 4.1, 95% CI = 1.9 to 8.9, $p = 0.001$) greater risk of subsequent
45 hamstring injury than players without such history. Between-limb imbalance in eccentric
46 knee-flexor strength of $\geq 15\%$ and $\geq 20\%$ increased the risk of hamstring strain injury 2.4
47 fold (RR = 2.4, 95% CI = 1.1 to 5.5, $p = 0.033$) and 3.4 fold (RR = 3.4, 95% CI = 1.5 to 7.6,
48 $p = 0.003$), respectively. Lower eccentric knee flexor strength and other prior injuries were
49 not associated with increased risk of future hamstring strain. Multivariate logistic regression
50 revealed that the risk of re-injury was augmented in players with strength imbalances.
51 **CONCLUSION:** Previous hamstring strain injury and between-limb imbalance in eccentric
52 knee-flexor strength were associated with an increased risk of future hamstring strain injury

53 in rugby union. These results support the rationale for reducing imbalance, particularly in
54 players who have suffered a prior hamstring injury, to mitigate the risk of future injury.

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56 **Key Terms**

57 Injury prevention; Muscle injuries; Nordic hamstring exercise; Physical
58 therapy/Rehabilitation; Rugby

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61 **What is known about the subject:**

62 Hamstring strain injury (HSI) is the most common cause of lost playing and training time in
63 professional rugby union and many of these injuries re-occur following a return to sport.
64 Eccentric knee flexor weakness and between-limb imbalances in eccentric knee flexor
65 strength have been associated with an increased risk of HSI in other sports, however, it
66 remains to be seen if these are risk factors for HSI in rugby union.

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68 **What this study adds to the existing knowledge:**

69 Rugby union players with between-limb imbalances in eccentric knee flexor strength in pre-
70 season, and those with a history of HSI, are at a significantly elevated risk of future HSI.
71 Moreover, for those players who have been injured previously, the risk of re-injury is
72 amplified when they also have between-limb strength imbalances. This study highlights the
73 multifactorial nature of HSI and supports the rationale for reducing strength imbalances,
74 particularly in those players who have suffered a prior HSI.

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77 INTRODUCTION

78 Rugby union is a physically demanding contact game with one of the highest reported
79 incidences of match injuries of all sports.^{7, 18, 40} The unique nature of the sport exposes
80 athletes of varying anthropometric characteristics⁴⁵ to frequent bouts of high-intensity
81 running, kicking, and unprotected collisions, interspersed with periods of lower intensity
82 aerobic work.¹⁴ Hamstring strain injury (HSI) represents the most common cause of lost
83 playing and training time at the professional level^{8, 9} and a significant portion of these injuries
84 re-occur, resulting in extended periods of convalescence.⁹

85 Despite the prevalence of HSIs in rugby union,⁸ efforts to identify risk factors and to optimise
86 injury prevention strategies are limited.^{9, 36} It is generally agreed that the aetiology of HSI is
87 multifactorial²⁴ and injuries result from the interaction of several modifiable^{10, 12, 13, 21, 28, 29, 33}
88 and non-modifiable^{2, 19, 20, 38} risk factors. In rugby union,⁹ as well as several other sports,^{3, 28,}
89 ⁴¹ HSIs most frequently result from high-speed running which potentially explains why the
90 incidence of HSI is significantly higher for backline rugby players , who perform longer and
91 more frequent sprints than forwards .⁹ During running, the biarticular hamstrings play a
92 crucial role in decelerating the forward swinging shank during terminal-swing⁴⁴ and in
93 generating horizontal force upon ground contact.²³ Given the active lengthening role of the
94 hamstrings it has been proposed that eccentric weakness²⁸ or between-limb imbalances in
95 eccentric strength may predispose to HSI, and both factors have been associated with the risk
96 of HSI in other sports.^{13, 15, 21, 29, 42} Furthermore, interventions aimed at improving eccentric
97 strength with the Nordic hamstring exercise reduce the incidence and severity of HSIs in
98 soccer^{1, 32} while professional rugby union teams employing the exercise have been reported to
99 suffer fewer HSIs than those which do not.⁹ Still, the role of eccentric strength in HSI
100 occurrence remains a controversial issue with contradictory results reported in the literature^{4,}
101 ⁴⁶ and a recent meta-analysis suggested that isokinetically-derived measures of strength do

102 not represent a risk factor for HSI.¹⁷ Nevertheless, the authors are not aware of any study that
103 has examined the relationship between eccentric knee-flexor strength, between-limb
104 imbalance, and HSI incidence in rugby union. Given the unique anthropometric
105 characteristics of rugby union players⁴⁵ and the diverse physical demands of the game,^{14, 40} it
106 may not be appropriate to generalise the findings from other sports to this cohort.

107 It has been shown that eccentric knee flexor strength can be reliably measured during the
108 performance of the Nordic hamstring exercise.²⁶ In a recent prospective study of elite
109 Australian footballers,²⁸ players with low Nordic strength measures in the pre-season training
110 period were significantly more likely to sustain an HSI in the subsequent competitive season.
111 However, it remains to be seen if the same measures can identify rugby union players at risk
112 of future HSI.

113 An improved understanding of risk factors for HSI in rugby union represents the first step³⁷
114 towards optimising injury prevention strategies and reducing the high rates of HSI occurrence
115 in the sport.^{8, 9} The aim of this study was to determine whether pre-season eccentric knee-
116 flexor strength and between-limb imbalance in strength measured during the Nordic
117 hamstring exercise, were predictive of future HSI in rugby union players. In addition, given
118 the multifactorial aetiology of HSI²⁴ and the potential for various risk factors to interact,³⁴ a
119 secondary aim was to determine the association between measures of eccentric strength,
120 imbalance and other previously identified risk factors, such as prior HSI.^{9, 34} The *a priori*
121 hypotheses were that subsequently injured players would display lower levels of eccentric
122 knee-flexor strength and greater between-limb imbalances in this measure than players who
123 remained free from HSI.

124 **METHODS**

125 **Participants & study design**

126 This prospective cohort study was approved by the Queensland University of Technology's
127 Human Research Ethics Committee and was completed during the 2014 Super 15 and
128 Queensland Rugby Union (QRU) seasons. In total, 194 male rugby players (age, 22.6 ± 3.8
129 years; height, 185 ± 6.7 cm; weight, 97 ± 13.1 kg) from three professional Super 15 clubs
130 ($n=75$) and two local QRU clubs ($n=119$) provided written informed consent to participate.
131 The QRU clubs included players in both sub-elite ($n=79$) and U'19 premier-grade teams
132 ($n=40$). Prior to the commencement of data collection, retrospective injury details were
133 collected for all players which included their history of hamstring, quadriceps and calf strain
134 injuries and chronic groin pain within the preceding 12 months as well as history of anterior
135 cruciate ligament (ACL) injury at any stage in their career. Demographic (age) and
136 anthropometric (height, body mass) data were also collected in addition to player position
137 (forward, back). For all Super 15 players these data were obtained from team medical staff
138 and the national Australian Rugby Union registry. All sub-elite players completed a standard
139 injury history form with their team physiotherapist and injuries were confirmed with
140 information from each club's internal medical reporting system. Subsequently, players had
141 their eccentric knee flexor strength assessed at a single time point within the 2014 pre-season
142 (Super 15, November 2013; sub-elite, January 2014). At the discretion of team medical staff,
143 some players ($n=16$) were excluded from strength testing because they had an injury or
144 illness at the time of testing that precluded them from performing maximal resistance
145 exercise

146 **Eccentric knee-flexor strength assessment**

147 The assessment of eccentric knee-flexor strength during the Nordic hamstring exercise has
148 been reported previously.^{26, 28} Participants knelt on a padded board, with the ankles secured
149 immediately superior to the lateral malleolus by individual ankle braces which were attached
150 to custom made uniaxial load cells (Delphi Force Measurement, Gold Coast, Australia) with

151 wireless data acquisition capabilities (Mantracourt, Devon, UK) (Figure 1). The ankle braces
152 and load cells were secured to a pivot which allowed the force generated by the knee flexors
153 to always be measured through the long axis of the load cells. Immediately prior to testing,
154 players were provided with a demonstration of the Nordic hamstring exercise from
155 investigators and received the following instructions: gradually lean forward at the slowest
156 possible speed while maximally resisting this movement with both limbs while keeping the
157 trunk and hips in a neutral position throughout, and the hands held across the chest²⁸.
158 Subsequently, players completed a single warm-up set of three repetitions followed by one
159 set of three maximal repetitions of the bilateral Nordic hamstring exercise. All trials were
160 closely monitored by investigators to ensure strict adherence to proper technique and players
161 received verbal encouragement throughout each repetition to encourage maximal effort. A
162 repetition was deemed acceptable when the force output reached a distinct peak (indicative of
163 maximal eccentric strength), followed by a rapid decline in force which occurred when the
164 athlete was no longer able to resist the effects of gravity acting on the segment above the
165 knee joint. All eccentric strength testing was performed in a rested state, prior to the
166 commencement of scheduled team training.

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170 **Data analysis**

171 Force data for the left and right limbs were transferred to a personal computer at 100Hz
172 through a wireless USB base station receiver (Mantracourt, Devon, UK). Eccentric strength,
173 determined for each leg from the peak force during the best of three repetitions of the NHE,

174 was reported in absolute terms (N) and relative to bodyweight ($\text{N}\cdot\text{kg}^{-1}$). For the uninjured
175 group, between limb imbalance in peak eccentric knee-flexor force was calculated as a
176 left:right limb ratio and for the injured group, as an uninjured:injured limb ratio. The between
177 limb imbalance ratio was converted to a percentage difference as per previous work²⁸ using
178 log transformed raw data followed by back transformation.

179

180 **Prospective hamstring strain injury reporting**

181 An HSI was defined as acute pain in the posterior thigh which caused immediate cessation of
182 training or match play and damage to the hamstring muscle-tendon unit²⁸ which was later
183 confirmed with magnetic resonance imaging (for all Super 15 players) or clinical examination
184 by the team physiotherapist (for all sub-elite and U'19 players). For all injuries that satisfied
185 the inclusion criteria, team medical staff provided the following details to investigators: limb
186 injured (left / right), muscle injured (biceps femoris long or short
187 head/semimembranosus/semitendinosus, injury severity (grade 1-3), injury mechanism (ie,
188 running, kicking, collision, change of direction), the date of injury and whether it was a
189 recurrence and the total time taken to resume full training and competition.

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191 **Statistical analysis**

192 All statistical analyses were performed using JMP 10.02 (SAS Institute, Inc). Mean and
193 standard deviations (SD) of age, height, weight, eccentric knee-flexor strength for the left
194 and right limb and between-limb imbalance (%) in strength were determined. Because the
195 player and not the leg was the unit of measure in some analyses, it was necessary to have a
196 single measure of eccentric knee-flexor strength for each athlete and this was determined by
197 averaging the peak forces from each limb (two-limb-average strength). Univariate analysis
198 was used to compare age, height, weight and between-limb imbalance between the injured

199 and uninjured groups. Eccentric knee-flexor strength of the injured limb was compared to the
200 uninjured contralateral limb and to the average of the left and right limbs from the uninjured
201 control group. In addition, eccentric knee-flexor strength was compared between elite, sub-
202 elite and U'19 players and between player positions (forwards vs. backs). All univariate
203 comparisons were made using independent samples t tests with Bonferroni corrections to
204 control for Type 1 error.

205

206 To calculate univariate relative risk (RR) and 95% confidence intervals (95% CI), players
207 were grouped according to:

208

- 209 • whether they did or did not have a history of
 - 210 ○ HSI in the previous 12 months
 - 211 ○ quadriceps strain injury in the previous 12 months
 - 212 ○ chronic groin pain in the previous 12 months
 - 213 ○ calf strain injury in the previous 12 months
 - 214 ○ or ACL injury at any stage;

- 215
- 216 • Two-limb-average eccentric knee-flexor strength above or below 267.9N or 3.18N.kg⁻¹
217 (these cut-offs were determined using receiver operator characteristic (ROC) curves
218 based on the force and relative force values that maximised the difference between
219 sensitivity and 1 – specificity).
- 220
- 221 • between-limb eccentric strength imbalance above or below a 10, 15 or 20% cut-off;
- 222
- 223 • whether they were above or below the 25th, 50th and 75th percentiles for:

- 224 ○ age
- 225 ○ height
- 226 ○ weight

227

228 Any variable associated with subsequent HSI according to univariate analysis was entered
229 into a univariate logistic regression model to determine its predictive value as a risk factor for
230 future HSI. Furthermore, given the multifactorial nature of HSI, a multivariate logistic
231 regression model was constructed (using prior HSI and between-limb imbalance) to explore
232 the potential interaction between risk factors²⁸ and eliminate any confounding effects.³⁰
233 Alpha was set at $p < 0.05$ and for all univariate analyses the difference between limbs and
234 groups is reported as mean difference and 95% CI.

235

236 **RESULTS**

237

238 **Cohort and prospective hamstring strain injury details**

239 In total, 178 players (age, 22.6 ± 3.8 years; height, 185 ± 6.8 cm; weight, 96.5 ± 13.1 kg) had
240 their eccentric knee-flexor strength assessed in the pre-season period. Of these, 75 were elite
241 (age, 24.4 ± 3.1 years; height, 186 ± 7.2 cm; weight, 101 ± 11.3 kg), 65 were sub-elite (age,
242 21.3 ± 3.7 years; height, 184 ± 6.4 cm; weight, 93 ± 13.4 kg) and 38 were in the U'19
243 division (age, 18.1 ± 0.8 years; height, 183 ± 6.8 cm; weight, 91 ± 14.9 kg).

244

245 Twenty athletes suffered at least one HSI during the 2014 competitive season (age, 22.8 ± 3.2
246 years; height, 185.6 ± 5.5 cm; weight, 97.4 ± 12.4 kg) and 158 remained free of HSI (age,
247 22.5 ± 3.8 years; height, 184.9 ± 7.0 cm; weight, 96.4 ± 13.3 kg). No significant differences
248 were observed in terms of age, height or body mass between the subsequently injured and

249 uninjured players ($p>0.05$). Hamstring strains resulted in an average of 21 days (range = 7 to
250 49 days) absence from full training and match play. Forty-five percent were recurrences from
251 the previous season and 25% of those reported during the observation period recurred. Of the
252 20 injuries, 80% affected the biceps femoris as the primary site of injury and 85% resulted
253 from high-speed running. The majority of HSIs were sustained by backs (60%) compared to
254 forwards (40%). No injuries were sustained during the assessment of eccentric knee-flexor
255 strength.

256

257 **Comparison of strength between playing level and position**

258 Eccentric strength measures for each level of play and player position can be found in Table
259 1. In terms of eccentric strength, there was no significant difference between elite and sub-
260 elite players (mean difference = 21N, 95% CI = -7.8 to 49.9N, $p = 0.154$) or between elite
261 and U'19 players (mean difference = 24.1N, 95% CI = -6.90 to 55.0 N, $p = 0.126$) however,
262 sub-elite players were significantly stronger than U'19 players (mean difference 45.1N, 95%
263 CI = 8.1 to 82.0N, $p = 0.017$). When expressed relative to bodyweight, both sub-elite (mean
264 difference = 0.35, 95%CI = 0.08 to 0.63, $p = 0.013$) and U'19 players (mean difference =
265 0.38N, 95%CI = 0.07 to 0.70, $p = 0.017$) were significantly stronger than elite players
266 although no difference was observed between sub-elite and U'19 players (mean difference = -
267 0.03, 95%CI = -0.4 to 0.34, $p = 0.870$). In absolute terms, forward line players were
268 significantly stronger than backs (mean difference = 35.3N, 95% CI = 10.11 to 60.5N, $p=$
269 0.006) however, no difference was observed when strength was normalised to bodyweight
270 (mean difference = -0.1, 95%CI = -0.35 to 0.16, $p = 0.583$).

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Univariate analysis of factors associated with hamstring strain injury

Eccentric knee-flexor strength and between-limb imbalances for the injured and uninjured groups can be found in Table 2. Limbs that went on to be injured were significantly weaker in pre-season than uninjured contralateral limbs both in absolute terms (mean difference = 55.1N, 95% CI = 11.65 to 98.5N, p=0.016) and when normalised to body mass (mean difference = 0.55 N.kg⁻¹, 95% CI = 0.13 to 0.98N.kg⁻¹, p = 0.013). Players who went on to sustain an HSI displayed higher levels of between-limb imbalance than those players who remained free from HSI (mean difference = -7.4%, 95% CI = -12.4 to -2.4%, p = 0.004). However, there was no difference between the subsequently injured limb and the average of the left and right limbs from the uninjured group either in absolute strength (mean difference = -14.9N, 95% CI = -55.5 to 25.6N, p = 0.470) or strength relative to body mass (mean difference = -0.07 N.kg⁻¹, 95% CI = -0.48 to 0.33 N.kg⁻¹, p = 0.710). No significant differences were observed in age (mean difference = 0.18yrs, 95% CI = -1.5 to 1.9yrs, p = 0.235), height (mean difference = 0.86cm, 95% CI = -2.3 to 4.1cm, p = 0.457), or weight (mean difference = 0.97kg, 95% CI = -5.2 to 7.4kg, p = 0.632) between the injured and uninjured groups.

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Relative risk

299 Players with a history of HSI in the previous 12 months had 4.1 (RR = 4.1, 95% CI = 1.9 to
300 8.9, p = 0.001) times greater risk of suffering a subsequent HSI than players with no HSI in
301 the same period (Table 2). Between-limb imbalance in eccentric knee-flexor strength of \geq
302 15% increased the risk of HSI 2.4 fold (RR = 2.4, 95% CI = 1.1 to 5.5, p = 0.033) while an
303 imbalance \geq 20% increased that risk 3.4 fold (RR = 3.4, 95% CI = 1.5 to 7.6, p = 0.003).
304 However, players with two-limb-average eccentric knee-flexor strength of less than 267.9N
305 were not at elevated risk of HSI (RR = 0.17, 0.0 to 2.7, p=0.204) compared to stronger
306 players (area under the ROC curve = 0.52; specificity= 0.86; sensitivity = 1.0). Similarly,
307 having normalised strength values of less than 3.18N.kg⁻¹ did not increase the risk of HSI
308 (RR = 0.97, 95%CI = 0.3 to 2.7, p = 0.957).

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314 **Logistic regression**

315 Players with a history of HSI in the previous 12 months were, according to the odds ratio, 5.3
316 times more likely (OR = 5.3, 95%CI = 1.84 to 15.0, p = 0.003) to suffer a subsequent HSI
317 than players who had remained injury free in that time. In addition, a relationship was
318 observed between the magnitude of between-limb imbalance in eccentric knee-flexor strength
319 and the risk of subsequent HSI; where, for every 10% increase in between-limb imbalance,
320 the odds of HSI increased by a factor of 1.34 (95%CI = 1.03 to 1.75, p=0.028) (Figure 2).

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Multivariate logistic regression revealed a significant (<0.001) relationship between both prior HSI and between-limb imbalance and the risk of subsequent HSI (Table 4), however, no interaction effect was observed between these variables. This model suggests that for players with a history of HSI, the risk of re-injury is amplified when they also have between-limb imbalances in eccentric knee flexor strength (Figure 2).

INSERT FIGURE 2

DISCUSSION

The aim of this study was to determine if rugby union players with lower levels of eccentric strength or larger between-limb imbalances in this measure, as determined during the Nordic hamstring exercise, were at increased risk of HSI. Higher levels of between-limb imbalance were found to significantly increase the risk of subsequent HSI and this was amplified in athletes who had suffered the same injury in the previous 12 months. However, while the limbs that went on to be injured were significantly weaker than the uninjured contralateral limbs in pre-season testing, weaker players were no more likely to suffer injury than stronger

347 players when strength was determined by averaging the peak eccentric forces from left and
348 right limbs.

349 The observation that higher levels of between-limb strength imbalance increase an athlete's
350 risk of HSI is consistent with previous reports.^{13, 15, 21, 29, 42} Croisier and colleagues reported
351 that professional soccer players with isokinetically-derived knee-flexor strength imbalances
352 in pre-season had a 4.66 fold greater risk of subsequent HSI than athletes without such
353 imbalances. More recently, Fousekis and colleagues found that elite soccer players with
354 imbalances in eccentric knee-flexor strength $\geq 15\%$ in the pre-season had a significantly
355 greater (OR = 3.88) risk of HSI than athletes with no asymmetry.¹⁵ Still, contradictory results
356 have been reported in Australian footballers^{4, 28} and it remains unclear as to the exact
357 mechanism(s) by which significant imbalances increase the risk of HSI. It is plausible that
358 between-limb imbalances in eccentric knee-flexor strength may alter running biomechanics¹¹
359 or reduce the capacity of the weaker limb to decelerate the forward swinging shank during
360 terminal-swing.²⁵ However, it should also be noted that the assessment of between-limb
361 imbalance in the current study was performed during a bilateral Nordic hamstring exercise,
362 whereas typical assessments involve maximal unilateral contractions performed on an
363 isokinetic dynamometer.^{4, 15} For this reason, direct comparisons to previous work should be
364 made with caution. A bilateral Nordic hamstring exercise was employed in the current study
365 as previous work has shown that this is more a more reliable test of eccentric knee-flexor
366 strength than unilateral Nordics.²⁶

367 The finding that weaker players were no more likely to sustain an HSI than stronger players
368 is in line with a recent systematic review and meta-analysis which suggested that
369 isokinetically-derived measures of strength were not a risk factor for HSI in sport.¹⁷
370 However, the results of the current study differ from a recent investigation²⁸ using the Nordic
371 hamstring test which reported that elite Australian footballer's with eccentric strength $<256\text{N}$

372 at the start of preseason and <279N at the end of preseason had a 2.7 and 4.3 fold greater risk
373 of HSI, respectively. The disparity between studies might reflect the vastly different
374 anthropometric characteristics of rugby union⁴⁵ and Australian football players,⁵ or the
375 unique physical demands of each sport.^{14,31} However, it is also important to consider that the
376 rugby players in the current study were substantially stronger than the Australian footballer's
377 studied previously.²⁸ It is possible that the protective benefits conferred by greater levels of
378 eccentric strength may plateau at higher ends of the strength spectrum as they appear to in
379 Australian footballer's (see Figures 1 & 2 in Opar et al.).²⁸ It should also be acknowledged
380 that while some studies have found an association between low levels of knee-flexor strength
381 and subsequent HSI,^{21, 28, 42} prior injury is also associated with knee-flexor weakness,^{12, 22, 26,}
382 ^{27, 35} and this may confound results.³⁰

383 The current study supports prior HSI as a risk factor for re-injury which is consistent with
384 earlier observations in rugby union^{9, 36} Australian football^{4, 16, 30, 39} and soccer.² While the
385 mechanism(s) explaining why prior HSI augments the risk of re-injury remain(s) unclear, this
386 study revealed a significant relationship between prior HSI and between-limb imbalance in
387 eccentric knee-flexor strength. This novel finding suggests that rugby union players with a
388 history of HSI have a significantly greater risk of re-injury if they return to training and
389 match play with one limb weaker than the other (Figure 2). For example, an athlete with a
390 prior HSI and a 30% between-limb imbalance in eccentric strength is twice as likely to suffer
391 a recurrence as a previously injured athlete with no imbalance. In light of this interaction,
392 there is a growing body of evidence to suggest that between-limb imbalance in knee-flexor
393 strength^{12, 13, 22, 29} is a risk-factor for HSI recurrence. These data highlight the multifactorial
394 nature of HSIs and suggest that the amelioration of between-limb imbalances in eccentric
395 knee-flexor strength should be a focus of rehabilitative strategies following HSI.

396 There are some limitations that should be acknowledged in the current study. Firstly, the
397 assessment of eccentric knee-flexor strength and between-limb imbalance was only
398 performed at a single time point in the pre-season period. While this is consistent with other
399 prospective studies exploring the impact of strength variables on HSI risk,^{13, 15, 21, 29, 42} it is
400 important to consider that strength may change over the pre-season and in-season periods.²⁸
401 The assessment of strength at multiple time points may provide a more robust measure of
402 player risk however, the geographic diversity of the Super 15 competition precluded follow-
403 up assessments by the investigators. Eccentric strength was measured as a force output (N)
404 rather than a joint torque (Nm) which makes direct comparison to isokinetically-derived
405 measures difficult. Further, this mode of testing does not allow for an assessment of the angle
406 at which the knee flexors produce maximum torque,⁶ and did not permit force to be expressed
407 relative to quadriceps¹³ or hip flexor⁴³ strength, which may provide additional information on
408 an athlete's risk of HSI. Finally, the lack of player exposure data prevents HSI rates being
409 expressed relative to the amount of training and match-play. Future work should seek to
410 clarify the effect of total exposure time (particularly to high-speed running) on the incidence
411 of HSI in rugby union players.⁹

412 In conclusion, this study suggests that both between-limb imbalances in eccentric knee-flexor
413 strength and prior HSI are associated with an increased risk of future HSI in rugby union.
414 However, lower levels of eccentric knee-flexor strength and a recent history of other lower
415 limb injuries do not significantly increase the risk of future HSI in this cohort. This study,
416 along with previous findings,²⁸ highlights the multifactorial nature of HSI and supports the
417 rationale for reducing imbalance, particularly in players who have suffered a prior injury
418 within the previous 12 months.

419

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424 patent application filed for the experimental device (PCT/AU2012/001041.2012).

425

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559 **Figure legends**

560 **Figure 1.** The Nordic hamstring exercise performed on the testing device (progressing from
561 right to left). Participants were instructed to lower themselves to the ground as slowly as
562 possible by performing a forceful eccentric contraction of their knee flexors. Participants only
563 performed the eccentric portion of the exercise and after ‘catching their fall’, were instructed
564 to use their arms to push back into the starting position (not shown here). The ankles are
565 secured independently.

566

567 **Figure 2.** The relationship between eccentric knee flexor strength imbalances and probability
568 of future hamstring strain injury (HSI) for players with and without a history of HSI in the
569 previous 12 months. Errors bars depict 95% confidence intervals.

570