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

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

Key Terms

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

What is known about the subject:

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

What this study adds to the existing knowledge:

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

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 characteristics[45] 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   multifactorial[24] 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-swing[44] 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 weakness[28] 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 players[45] 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 step[37]

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 HSI[24] 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 chest[28].

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.

167

168   INSERT FIGURE 1

169

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 (N.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 work[28] 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 unit[28] 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.

190

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   o HSI in the previous 12 months

211   o quadriceps strain injury in the previous 12 months

212   o chronic groin pain in the previous 12 months

213   o calf strain injury in the previous 12 months

214   o 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   o   age

225   o   height

226   o   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 factors[28] 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).

271

272

273   INSERT TABLE 1

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275

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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.

293

294

INSERT TABLE 2

296

297

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).

309

310

311   INSERT TABLE 3

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313

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).

321

322

323   INSERT TABLE 4

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325

326 Multivariate logistic regression revealed a significant (<0.001) relationship between both

327 prior HSI and between-limb imbalance and the risk of subsequent HSI (Table 4), however, no

328 interaction effect was observed between these variables. This model suggests that for players

329 with a history of HSI, the risk of re-injury is amplified when they also have between-limb

330 imbalances in eccentric knee flexor strength (Figure 2).

331

332

333   INSERT FIGURE 2

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337

338 **DISCUSSION**

339

340 The aim of this study was to determine if rugby union players with lower levels of eccentric

341 strength or larger between-limb imbalances in this measure, as determined during the Nordic

342 hamstring exercise, were at increased risk of HSI. Higher levels of between-limb imbalance

343 were found to significantly increase the risk of subsequent HSI and this was amplified in

344 athletes who had suffered the same injury in the previous 12 months. However, while the

345 limbs that went on to be injured were significantly weaker than the uninjured contralateral

346 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 ≥ 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 biomechanics[11]
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 investigation[28] using the Nordic
371 hamstring test which reported that elite Australian footballer's with eccentric strength <256N

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 union[45] 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 quadriceps[13] or hip flexor[43] 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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558

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