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1 **TITLE**

- 2 Knee flexor strength and bicep femoris electromyographical activity is lower in previously
- 3 strained hamstrings.
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21 INTRODUCTION

Hamstring strain injuries, characterised by acute pain in the posterior thigh and disruption of
hamstring muscle fibres, are the primary injury sustained in a number of sports [Orchard &
Seward, 2010; Woods et al., 2004; Drezner et al., 2005] and re-injury rates are also high
[Orchard & Seward, 2010]. The high rate of injury and re-injury, combined with the fact that
a previous hamstring strain injury is the most significant risk factor for future injury [Arnason
et al., 2004], suggests that our understanding of the neuromuscular maladaptations that occur
following hamstring strain requires further attention.

Previous hamstring strain injury has been associated with between-limb differences in 29 eccentric strength that is typically greater than concentric strength deficits [Croisier et al., 30 31 2002; Lee et al., 2009]. Furthermore these deficits in eccentric strength are still present despite athletes returning to full training and competition [Croisier et al., 2002; Lee et al., 32 2009]. Whilst the retrospective nature of these findings cannot be taken to suggest that 33 34 hamstring injury has resulted in these deficits, it is agreed that hamstring strain injury does 35 lead to maladaptation [Opar et al., 2012]. Importantly, prospective studies in both sprinters and soccer players have identified eccentric knee flexor strength deficits as elevating 36 hamstring strain injury risk [Croisier et al., 2008; Sugiura et al., 2008]. These findings 37 suggest the importance of eccentric strength for the prevention of hamstring strain injury and 38 that eccentric weakness should be corrected following injury to reduce the risk of a 39 recurrence. However a clear understanding of the mechanisms underpinning the decline in 40 eccentric strength following hamstring strain injury is required in order to develop more 41 42 appropriate exercise interventions. Whilst evidence does exist of persistent atrophy of biceps femoris long head (BF) up to 23 months following grade I and II hamstring strain injuries 43 [Silder et al., 2008] this muscular maladaptation does not explain why the decline in 44

hamstring strength appears to be greater in eccentric actions [Croisier et al., 2002; Lee et al.,
2009].

47

Surprisingly the impact of strain injuries on the neural function of the involved musculature 48 has been largely overlooked. Hamstring strain injury has been reported to result in acute 49 [Verrall et al., 2001] and chronic pain [Croisier et al., 2002; Jönhagen et al., 1994]. This 50 muscular pain also has the potential to alter central nervous function at both the spinal and 51 supraspinal level [Mense, 2003], and might therefore be expected to result in a restriction of 52 electromyographical activity and the median power frequency of this activity during 53 contraction. Furthermore this restriction may be specifically confined to the muscle and 54 55 contraction mode responsible for the noxious stimulus. Therefore the purpose of this study was to assess concentric and eccentric hamstring torque, surface EMG (sEMG) activity and 56 the median power frequency of the sEMG signal of recreational athletes with and without a 57 58 history of unilateral hamstring strain injury. It was hypothesised that the previously injured 59 hamstrings would display strength, sEMG activity and median power frequency deficits during fast and slow eccentric contractions, but not concentric contractions, compared to the 60 contralateral limb. Furthermore, we hypothesised that lower levels of sEMG activity and 61 median power frequency would be confined specifically to the previously injured hamstring 62 muscle (i.e. BF or medial hamstrings (MH)). It was also hypothesised that the control group 63 would display no differences in any of the aforementioned variables between dominant and 64 non-dominant limbs. As a confirmatory secondary analysis, it was also hypothesised that the 65 between limb differences in eccentric hamstring torque, sEMG and median power frequency 66 would be greater in previously injured athletes compared to the control group. 67

68

69 MATERIALS AND METHODS

70 Participants

Twenty-eight recreationally active males participated in the study, with most competing in 71 Australian football, rugby, soccer or sprinting. Thirteen athletes $(26.2 \pm 5.8 \text{ years}; 1.80 \pm$ 72 0.04m; $83.0 \pm 14.8kg$) had at least one unilateral hamstring strain injury (INJ) within the last 73 18 months and all had suffered a grade II injury previously. Another 15 athletes (26.7 ± 5.8) 74 years; 1.8 ± 0.05 m; 83.5 ± 7.9 kg) had no history of hamstring strain injury (UI). All 75 participants were free of any other injury to the lower limbs and were fully active in their 76 chosen sport at the time of testing. All testing procedures were approved by the University 77 78 Human Research Ethics Committee. Participants gave informed written consent prior to testing after having all procedures explained to them. 79

80 Injury questionnaire

Following recruitment, participants completed an injury questionnaire with their chosen 81 82 practitioner (i.e. physiotherapist) who had previously diagnosed and treated all the athletes 83 hamstring strain injury. As per previous investigations [Sole et al., 2011], the notes taken from clinical examination were used to detail the date of injury and return to pre-injured 84 levels of training and competition, severity (grade I, II or III) [Blankenbaker & Tuite, 2010], 85 location (dominant or non-dominant limb; BF or MH head; proximal or distal) and 86 rehabilitation details of all previous hamstring strain injuries. Limb dominance was 87 determined as the preferred kicking limb. Athletes were considered to be successfully 88 rehabilitated when they returned to pre-injured levels of training and were available for 89 90 competition [Fuller et al., 2006]. Athletes who were unable to obtain data on all prior hamstring strains from their practitioner were excluded from the study. 91

92 **EMG recording**

Bipolar pre-gelled Ag/AgCl sEMG electrodes (10mm diameter, 25mm inter-electrode 93 distance) were used to record electromyographical activity from the MH and BF. After 94 preparation of the skin via shaving, light abrasion and sterilisation, electrodes were placed on 95 the posterior thigh half way between the ischial tuberosity and tibial epicondyles with 96 electrodes oriented parallel to the line between these two land marks, as per SENIAM 97 guidelines [Hermens et al., 2000]. The reference electrode was placed on the ipsilateral head 98 of the fibula. Muscle bellies were identified via palpation during forceful isometric knee 99 100 flexion and correct placement was confirmed by observing sEMG activity during active internal and external rotation of the flexed knee to assess cross talk between MH and BF. 101

102 Isokinetic dynamometry

Assessment of concentric and eccentric knee flexor strength was performed on a Biodex 103 104 Systems 3 Dynamometer (Biodex Medical Systems, Shirley, NY). Participants were seated on a custom pad, placed on top of the original seat, which contained two holes at the level of 105 the posterior mid thigh to minimise movement artefact from sEMG electrodes on the 106 dynamometer seat. The hips were flexed at 85° from neutral with the lateral epicondyle of the 107 femur carefully aligned with fulcrum of the dynamometer. The tested leg was attached to the 108 109 lever of the dynamometer via a Velcro strap and padded restraints were fastened across the trunk, hips and mid thigh of the tested leg to isolate movement to the knee joint. The range of 110 motion was set at 5°-90° of knee flexion (0°=full knee extension) and correction for limb 111 weight was performed. 112

113 Three sets of four submaximal contractions of the knee extensors and flexors were performed 114 at $+240^{0}$.s⁻¹ as a warm-up to prepare the participant for maximal effort in the following sets. 115 Concentric testing for both legs consisted of three sets of three consecutive maximum

voluntary contractions (MVC) of the knee extensors and flexors at velocities of $+60^{\circ}$.s⁻¹ and 116 $+180^{\circ}$.s⁻¹ with 30 seconds rest between sets. Athletes were motivated verbally by the 117 investigators to encourage maximal effort throughout the range of motion. Eccentric testing (-118 60° .s⁻¹ and -180[°].s⁻¹) was identical except that only eccentric contraction of the knee flexors 119 was performed by the participant (whereby the knee joint was extended despite active 120 contraction of the knee flexors) and at the completion of each contraction the investigators 121 returned the lever to the starting position. The leg and velocity testing orders were 122 randomised but concentric contractions were always performed before eccentric contractions. 123 124 All participants were required to attend at least one familiarisation session to ensure consistency of MVCs and one testing session with \geq seven days between sessions. 125

126 Data analysis

Dynamometer torque and lever position data were transferred to computer at 1 kHz and 127 stored for later analysis. Average peak torque was defined as the mean maximal torque of the 128 six highest torque contractions at each velocity. Surface EMG was sampled simultaneously 129 with dynamometer data at 1kHz through a 16-bit PowerLab26T AD recording unit 130 (ADInstruments, New South Wales, Australia) (amplification = 1000 between 10Hz-1kHz; 131 common mode rejection ratio = 110dB) and stored for later analysis where it was fourth order 132 Butterworth filtered between 20-500Hz (24dB roll off) using MATLAB (MathWorks, Natick, 133 Massachusetts) and then full wave rectified using the root-mean-square method across a 134 100ms window. At each velocity, sEMG data were averaged across a knee joint ROM 135 between 15°-35° as this is where deficits in sEMG have been noted previously [Sole et al., 136 2011]. Data at all velocities was then normalised to the maximal averaged sEMG amplitude 137 recorded during MVCs at +180[°].s⁻¹ [Aagaard et al., 2002; Seger et al., 1994; Westing et al., 138 1991]. For this process the data was separated in tertiles throughout the ROM (15°-35°, 35° -139

 60° , 60° - 80°) and the tertile exhibiting the highest amplitude of sEMG was used for 140 normalisation. Median power frequency was determined from the non-rectified sEMG signal 141 via Fast Fourier transform with Hann window function applied [Aagaard et al., 2000] across 142 the entire ROM using LabCart 7.3 (ADInstruments, New South Wales, Australia) with 1Hz 143 frequency resolution. This resulted in 1.08 and 0.36 second time epochs for analysis of 144 contractions at ± 60 and 180° .s⁻¹ respectively. Median power frequency was analysed over a 145 larger ROM (15-80°) than sEMG activity to allow for a valid estimation of frequency. 146 Median power frequency was defined as the frequency at which 50% of total power was 147 148 reached for each time epoch.

149 Statistical analysis

150 Data were analysed using JMP version 10.0 Pro Statistical Discovery Software (SAS Inc). In the primary analysis, comparisons were made between the injured and uninjured limbs in the 151 INJ group and between dominant and non-dominant limbs in the UI group. Dependent 152 variables were compared using one tailed paired t tests for both groups to allow an equal 153 154 likelihood for finding significant differences between limbs [Lee et al., 2009]. Data are presented as means and standard deviation. Bonferroni corrections were performed to account 155 for four comparisons made for each dependent variable across the velocities used, with 156 significance set at p < 0.0125. In the confirmatory secondary analysis independent t tests for 157 unequal variance were used to compare the between limb differences of the dependent 158 variables in the INJ (uninjured limb minus injured limb) and UI groups (dominant limb minus 159 non-dominant limb) as assumptions for equal variance between groups was not met. For the 160 161 secondary analysis significance was set at p < 0.05 and data are presented as mean differences and 95% confidence intervals. To assess the magnitudes of the differences for the 162 primary and secondary analyses Cohen's d was calculated to report effect size (ES). 163

164 **RESULTS**

165 **Participants**

166 There was no significant difference between the UI and INJ groups with respect to age,

167 height or body mass. The details of injury histories of all athletes from the INJ group can be

168 found in Table 1. All athletes from the INJ group reported largely standard rehabilitation

169 progression (i.e. [Heiderscheit et al., 2010]) guided by their physiotherapist.

170 Average peak torque

There were significant differences in average peak torque between limbs in the INJ group,
with the previously injured limb weaker at all contraction modes and velocities (Figure 1a &
Table 2). No differences in average peak torque were noted between limbs in the UI group
(Figure 1b & Table 2). Between limb differences in torque were significantly greater in the
INJ group compared to the UI group at all contraction modes and velocities, except for
concentric contractions at 180⁰.s⁻¹ (Table 5).

177 sEMG activity

Biceps femoris long head electromyographical activity was significantly lower in the 178 previously injured limb compared to the contralateral uninjured limb in the INJ group during 179 eccentric contractions but not concentric contractions (Figure 2a & Table 3). There were no 180 differences between limbs in the INJ group for MH electromyographical activity at any 181 contraction mode or velocity (Figure 3a & Table 3). In the UI group there were no 182 differences in activation between limbs for BF (Figure 2b & Table 3) or MH (Figure 3b & 183 Table 3) at any contraction mode or velocity. Between limb differences in 184 electromyographical activity were greater in the INJ group compared to the UI group only for 185

BF at -180° .s⁻¹ (Table 5). All other between limb differences in electromyographical activity were similar between INJ and UI groups, although a trend existed at -60° .s⁻¹ (Table 5).

188 Median power frequency

One participant from the INJ group was a clear outlier (median power frequency was more than 3 standard deviations above the mean for eccentric contractions) and was removed from analysis. There were no differences in median power frequency at any velocity between legs in the INJ group for BF or MH (Table 4). A similar lack of differences was noted at all velocities for the UI group for BF or MH median power frequency (Table 4). The between limb differences in median power frequency did not differ between the INJ and UI groups at any contraction mode or velocity (Table 5).

196 **DISCUSSION**

It is accepted that a prior hamstring strain injury results in maladaptation of the previously 197 injured tissue [Opar et al., 2012]. Whilst a number of muscular maladaptations have been 198 reported previously [Brockett et al., 2004; Croisier et al., 2002; Lee et al., 2009; Silder et al 199 2008; Silder et al., 2010; Worrell et al., 1991], the impact of a prior hamstring strain injury on 200 neural function has been scarcely examined [Sole et al., 2011]. The current study used 201 between limb comparisons of normalised sEMG activity and median power frequency to 202 determine differences in neural hamstring function between injured and uninjured limbs. This 203 method eliminates a number of confounding factors by ensuring that muscle lengths and 204 electrode locations are identical between trials within and between limbs and has been used 205 206 extensively to assess relative muscle activation in maximal concentric and eccentric contraction [Aagaard et al., 2002; Seger et al., 1994; Westing et al., 1991]. 207

From the INJ group in the current study, the novel findings were that the previously injured 208 limb, when compared to the contralateral uninjured limb displayed 1) a lower level of sEMG 209 activity specifically in the previously injured muscle (BF) during slow and fast eccentric 210 contractions (Figure 2a & Table 3); and; 2) there was no difference in the median power 211 frequency in either the previously injured BF or uninjured MH (Table 4). Furthermore, lower 212 levels of strength were observed across all contraction modes and velocities in the injured 213 limb compared to the uninjured limb in the INJ group (Figure 1a). In contrast the control 214 group showed no differences between dominant and non-dominant limbs in any of the tested 215 216 variables indicating there is no influence of limb dominance (Figure 1b, 2b, 3b; Table 2, 3, 4). These findings were mostly supported by confirmatory analysis which indicated that the 217 between limb differences in knee flexor torque at all contraction modes and velocities, except 218 219 for the fastest concentric contractions, and BF sEMG during fast eccentric contraction was greater in INJ group compared to the UI group (Table 5). 220

This study is, to our knowledge, the first to identify lower levels of sEMG activity 221 specifically in the previously injured BF muscle compared to a contralateral uninjured BF. 222 Recent evidence examining a similar phenomenon did not find a muscle specific, between 223 limb differences in sEMG activity following a hamstring strain injury [Sole et al., 2011]. The 224 discrepancies between the findings from the current study and the previous study by Sole and 225 colleagues (2011) work may be attributed to the inclusion of athletes with bilateral injury 226 histories which may have contributed to the lack of difference in sEMG activity between the 227 injured leg and the contralateral control limb in earlier work [Sole et al., 2011]. However our 228 finding that, when comparing BF sEMG across the two groups, only during eccentric 229 contractions at -180[°].s⁻¹ was the between limb difference significantly greater in the INJ 230 compared to the UI group, somewhat confirms a previous similar finding by Sole et al. 231

232 (2011). Whilst there was no significant between limb difference in BF sEMG during 233 eccentric contractions at -60° .s⁻¹ when comparing the two groups in the current study, the 234 large ES (d=0.74) indicates that a significant difference may have existed with an increased 235 sample size.

Reductions in muscle activation during eccentric contractions is due to reduced motor unit 236 recruitment and/or firing rates [Webber & Kriellaars 1997] which impact upon maximal 237 238 torque generation capabilities. Following hamstring strain injury it has been suggested that the purpose of reduced hamstring activation would be to protect the damaged tissue from 239 high force contraction [Opar et al., 2012]. Hamstring strain injuries themselves are 240 241 characterised by acute pain in the posterior thigh [Verrall et al., 2001] with reports of chronic pain not uncommon [Croisier et al., 2002; Jönhagen et al., 1994] and this has the potential to 242 result in long-term re-organisation of the nervous system at the spinal and supraspinal levels 243 244 [Mense, 2003]. The current study confirms that, even in athletes who have been successfully rehabilitated and have returned to competition, sEMG activity of the BF remains suppressed. 245 This would indicate that, for the current cohort, contemporary rehabilitation practices were 246 unsuccessful at addressing deficits in the activation of BF. This is of concern from the 247 perspective of HSI recurrence given submaximal stimulation of *in-situ* animal muscle reduces 248 249 the amount of stress that muscle can withstand before the occurrence of stretch induced failure [Garrett et al., 1987]. This may indicate that the previously injured BF is unable to 250 withstand the same amount of stress before failure compared to an uninjured muscle, thus 251 increasing the likelihood of re-injury. The observation of no between limb differences in 252 median power frequency in the INJ group suggests that prior hamstring strain injury may not 253 impact upon average muscle fibre conduction velocity [Linnamo et al., 2000]. It should also 254 be acknowledged that a number of other factors also influence the median power frequency 255

of the electromyographical signal and further investigation examining these factors discretelyis warranted.

It has been proposed previously that the suppression of hamstring muscle activation 258 following hamstring strain injury has the potential to limit adaptation during the rehabilitation 259 process [Opar et al., 2012]. This model suggests early to middle stage rehabilitation for 260 hamstring strain injury typically involves avoidance of excessive stretching of the involved 261 tissue and submaximal exercise performed through limited range of motion in an attempt to 262 prevent proliferation of scar tissue [Heiderscheit et al., 2010]. Such an approach might be 263 expected to result in a reduction of in-series sarcomeres [Williams & Goldspink, 1978] and 264 induce atrophy [Silder et al., 2008] potentially reducing the optimal length of the hamstrings 265 [Brockett et al., 2004] which would be unfavourable given the need for the hamstrings to 266 generate high eccentric forces at relatively long muscle lengths in running [Thelen et al., 267 268 2005]. Late stage rehabilitation involving more forceful eccentric contractions at long muscle lengths might be expected to overcome these maladaptations [Lynn & Morgan, 1994], 269 270 however, suppression of hamstring activation, as reported in the current study, would reduce the stimulus the previously injured muscle is exposed to, thus potentially compromising the 271 adaptive response to rehabilitation. The present study suggests that chronic lowering of 272 hamstring activation following strain injury could sabotage the rehabilitation process. Still, 273 the full impact of prior hamstring strain injury on neurological control of the involved 274 muscle/s and impact on adaptation requires further attention. 275

The current study found strength at all velocitiess and contraction modes was lower in the previously injured limb compared to the uninjured limb. Previous work has found eccentric but not concentric declines in strength [Lee et al., 2009] or greater eccentric deficits (22-24%) compared to concentric deficits (10-11%) following hamstring strain injury [Croisier et al.,

2002]. As muscle shortening velocity is known to influence maximal tension generating 280 capacity [Fenn & Marsh, 1935] the different concentric velocities used in previous work may 281 explain the inconsistent findings for this contraction mode. In line with this, the percentage 282 283 difference in strength between previously injured and uninjured limbs tested at a comparable velocities (+60⁰.s⁻¹) is similar in the current study (10.9%) and previous work (11%) [Croisier 284 et al., 2002]. The much larger decline in eccentric strength reported elsewhere [Croisier et al., 285 2002] is less likely to be due to differences in eccentric testing velocities as eccentric strength 286 is largely unaffected by lengthening velocity. It may be, however, explained by differences in 287 288 rehabilitation practices of the respective cohorts given the greater appreciation for eccentric conditioning in hamstring strain injury prevention in recent times [Petersen et al., 2011]. 289 Perhaps not surprisingly, more recent studies have reported smaller eccentric strength 290 291 differences in the order of 13% [Lee et al., 2009], which is comparable to the 10.9-12.5% differences reported in the current study. 292

Uniformly lower concentric and eccentric strength, as observed in the current study, would be 293 expected if strength was determined solely from muscle cross sectional area and volume, 294 given the noted atrophy of BF following hamstring strain injury [Silder et al., 2008]. 295 Interestingly, sEMG activity was lower only during eccentric contractions, despite lower 296 strength across contraction modes and velocities. This suggests that reductions in BF activity 297 contribute to prolonged eccentric, but not concentric, weakness following hamstring strain 298 injury. It might therefore be expected that the decline in eccentric strength following 299 hamstring strain injury would be of a greater relative magnitude than concentric strength, but 300 this is not supported by the current data. It may be that other muscles which contribute to 301 knee flexion, that were not examined in the current study, such as the short head of biceps 302 femoris, gastrocnemius and sartorius, increase their involvement during maximal eccentric 303

contraction in a previously injured leg to help overcome the limitation in sEMG activity of
BF. Indeed, compensatory hypertrophy of the short head of biceps femoris has been reported
previously [Silder et al., 2008], suggesting hamstring strain injury may lead to increased use
of uninjured musculature, however further examination of this area is warranted.

There are some limitations in the present study's methodology. The retrospective nature of 308 the study does not allow for the determination of whether the reduction in sEMG activity of 309 BF is the cause of or the result of injury. Prospective studies are required to determine if low 310 levels of BF activity elevates the risk of sustaining a future hamstring strain injury. It should 311 be noted, however, that whilst prospective studies have determined that a between limb 312 eccentric strength difference of approximately 4.5% is associated with future hamstring strain 313 injury [Suguiura et al., 2008], post-injury eccentric weakness is reported to be between 13-314 24% [Croisier et al., 2002; Lee et al, 2009], suggesting hamstring injury enhances eccentric 315 knee flexor weakness, most probably via neuromuscular maladaptation. Also using the 316 maximal activation data from the fastest concentric movement velocity $(+180^{\circ}.s^{-1})$ to 317 normalise the sEMG data as per previous investigations [Aagaard et al., 2000] has the 318 potential to mask any between-limb differences in sEMG activity at this velocity, however 319 given the important nature of eccentric strength in hamstring strain injury aetiology, sEMG 320 activity during eccentric contraction was of most interest. Finally, the power of the current 321 study may have been too small to detect between limb differences in variables not determined 322 to be significantly different in current study. We have reported ES for all comparisons (Table 323 2-4) to further illustrate the strength of the between limb differences. The ES data suggests 324 that, in particular, the study may have been underpowered to detect differences in the 325 electromyographical activity of the MH and the median power frequency between injured and 326

327	uninjured limbs. A larger sample size should be a consideration for future work,
328	notwithstanding the difficulty in recruiting athletes for the INJ group.
329	In conclusion, this study is the first to report that athletes with a history of unilateral
330	hamstring strain injury display reductions in the sEMG activity of a previously injured BF
331	during eccentric contractions and no difference in the median power frequency of either
332	hamstring head during concentric or eccentric contractions. Furthermore strength was
333	suppressed during both contraction modes in the injured limb compared to the uninjured
334	limb. Previous hamstring strain injury may result in between limb alterations in
335	neuromuscular function and rehabilitation practices need to consider the recovery of strength
336	and activation during eccentric contractions as markers of successful rehabilitation as this
337	may assist in reducing the incidence of hamstring strain injury recurrence.
338	
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342	
343	CONFLICT OF INTEREST
344	NA
345	
346	

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TABLES

Subject	ct Time since HSI Rehabilitation duration		Location	Total HSIs sustained	
	(months)	(weeks)			
1	2	4	Dominant, Proximal BF	1	
2	3	4	Non dominant, Proximal BF	3	
3	8	4	Non dominant, Distal BF	1	
4	7	2	Non dominant, Proximal BF	2	
5	3	4	Dominant, Proximal BF	4	
6	5	2	Non dominant, Distal BF	2	
7	18	4	Non dominant, Distal BF	1	
8	4	4	Non dominant, Proximal BF	2	
9	2	5	Non dominant, Proximal BF	2	
10	5	3	Non dominant, Proximal BF	4	
11	2	2	Dominant, Proximal BF	2	
12	3	6	Non dominant, Distal BF	4	

Table 1. Hamstring strain injury information for most recent injury for athletes recruited to the injured group.

	13	7	3	Non dominant, Proximal BF	3	
476	HSI, hamstring	g strain injury; BF, b	iceps femoris. All prior injurio	es were confined to the same leg and mu	scle as most recent inju	ry however location on
477	muscle (proxir	mal or distal) differed	1 in some instances.			
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Movement velocity (°.s ⁻¹)	Injured Group	Injured Group			
	Injured limb	Uninjured limb	р	ES	
+180	109.29 (± 13.14)	118.64 (± 12.47)	0.0036*	0.78	
+60	132.00 (± 21.28)	146.01 (± 15.49)	0.0013*	0.70	
-60	166.76 (± 30.19)	185.02 (± 25.22)	0.0007*	0.57	
-180	163.82 (± 30.43)	184.37 (± 22.33)	0.0007*	0.74	
		Uninjured group			
	Dominant limb	Non-dominant limb	р	ES	
+180	127.13 (± 22.12)	122.73 (± 21.24)	0.0608	0.20	
+60	154.93 (± 24.27)	151.59 (± 25.10)	0.1558	0.14	
-60	199.71 (± 31.46)	198.68 (± 33.30)	0.4341	0.03	
-180	194.84 (± 25.97)	194.60 (± 28.84)	0.4828	0.01	

488 Table 2. Knee flexor torque of athletes with and without a history of unilateral hamstring strain injury 489 during concentric and eccentric contraction.

490 Negative movement velocities are indicative of eccentric contractions and positive velocities indicate
 491 concentric contractions. Data are presented as mean (± standard deviation). *Significance was set at p

492 <0.0125. Cohen's d was used to calculate effect size.

Movement velocity (°.s ⁻¹)				Injure	d group			
		Biceps femoris			М	edial hamstrings		
	Injured limb	Uninjured limb	Р	ES	Injured limb	Uninjured limb	Р	ES
+180	0.96 (±0.06)	0.99 (± 0.02)	0.0894	a	0.95 (± 0.07)	0.98 (± 0.06)	0.0622	a
+60	0.89 (± 0.20)	0.93 (± 0.12)	0.2255	0.18	0.91 (± 0.23)	0.96 (± 0.13)	0.2412	0.09
-60	0.58 (± 0.17)	0.71 (± 0.17)	0.0025*	0.47	0.58 (± 0.21)	0.64 (± 0.12)	0.1296	0.06
-180	0.53 (± 0.20)	0.66 (± 0.18)	0.0003*	0.58	0.52 (± 0.22)	0.61 (± 0.15)	0.0770	0.26
				Uninjur	ed group			
		Biceps femoris				Medial hamstrings		
	Dominant limb	Non-dominant limb	Р	ES	Dominant limb	Non-dominant limb	Р	ES
+180	0.97 (± 0.06)	0.99 (± 0.02)	0.1602	а	0.94 (± 0.11)	0.94 (± 0.12)	0.4444	a
+60	0.95 (± 0.16)	0.97 (± 0.18)	0.2703	-0.12	0.93 (± 0.26)	0.97 (± 0.23)	0.2890	-0.16
-60	0.70 (± 0.21)	0.69 (± 0.17)	0.4275	0.05	0.64 (± 0.25)	0.67 (± 0.16)	0.3077	-0.14
-180	0.60 (± 0.26)	0.61 (± 0.14)	0.4052	-0.05	0.56 (± 0.23)	0.59 (± 0.15)	0.2538	-0.15

Table 3. Normalised electromyographical activity of the biceps femoris long head and medial hamstrings of athletes with and without a history of unilateral
 hamstring strain injury during concentric and eccentric contraction.

499 500 501 502 503 504 505 506 507 508 509 509 501 502 503 504 505 506 507 508 509 501 502 503 504 505 506 507 508 509 501 502 503 504 505 506 507 508 509 500 501 502 503 504 505 506 507 508 509 500 500 500 500 5	496 497 498	Negative movement velocities are indicative of eccentric contractions and positive velocities indicate concentric contractions. Data are presented as mean (\pm standard deviation). *Significance was set at p < 0.0125. Cohen's d was used to calculate effect size (ES). ^a ES for electromyographical activity could not be calculated given the use of this data in the normalisation process.
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Movement velocity (°.s ⁻¹)	t velocity (°.s ⁻¹) Injured group							
		Biceps femoris			Mec	Medial hamstrings		
	Injured limb	Uninjured limb	Р	ES	Injured limb	Uninjured limb	Р	ES
+180	61.70 (± 5.82)	64.70 (± 9.00)	0.1005	0.40	67.75 (± 6.25)	71.15 (± 8.34)	0.1680	0.47
+60	60.30 (± 6.64)	62.11 (± 7.80)	0.2220	0.25	58.70 (± 7.48)	62.78 (± 9.57)	0.1655	0.48
-60	64.78 (± 7.83)	66.92 (± 9.35)	0.2530	0.24	62.85 (± 9.63)	66.03 (± 15.53)	0.2950	0.25
-180	63.04 (± 6.38)	68.03 (± 13.73)	0.1030	0.50	64.68 (± 9.42)	70.43 (± 18.49)	0.2140	0.41
				Uninj	ured group			
		Biceps femoris				Medial hamstrings		
	Dominant limb	Non-dominant limb	Р	ES	Dominant limb	Non-dominant limb	Р	ES
+180	63.57 (± 11.35)	62.82 (± 7.41)	0.3580	0.08	74.84 (± 13.24)	72.04 (± 7.71)	0.2460	0.26
+60	62.71 (± 7.60)	62.84 (± 7.51)	0.4670	-0.02	69.44 (± 10.44)	66.28 (± 6.28)	0.1025	0.37
-60	63.25 (± 9.37)	63.38 (± 6.89)	0.4620	-0.02	70.24 (± 15.52)	66.42 (± 13.50)	0.2075	0.26
-180	64.22 (± 12.62)	66.05 (± 8.26)	0.2400	-0.17	70.21 (± 18.21)	71.05 (± 13.62)	0.4275	-0.05

Table 4. Median power frequency of the biceps femoris long head and medial hamstrings of athletes with and without a history of unilateral hamstring
 strain injury during concentric and eccentric contraction.

517 Negative movement velocities are indicative of eccentric contractions and positive velocities indicate concentric contractions. Data are presented as mean

518 (\pm standard deviation). Significance was set at p < 0.0125. Cohen's d was used to calculate effect size (ES).

519 Table 5. Comparison of between limb differences in knee flexor torque and normalised electromyographical activity and median power frequency of the

- 520 biceps femoris long head and medial hamstrings in athletes with and without a history of hamstring strain injury, during concentric and eccentric
- 521 contraction.

Movement velocity (°.s ⁻¹)	Knee flexor torque									
	Injured group	Uninjured group	Р	ES						
+180	9.34 (3.03 to 15.66)	4.40 (-1.33 to 10.13)	0.2208	0.48						
+60	14.01 (5.98 to 22.02)	3.34 (-3.48 to 10.16)	0.0379*	0.83						
-60	18.26 (8.68 to 27.84)	1.03 (-12.10 to 14.17)	0.0312*	0.85						
-180	20.55 (9.72 to 31.37)	0.24 (-11.56 to 12.04)	0.0110*	1.03						
		Ν	lormalised el	ectromyog	raphical activity					
	Biceps femoris				Medial hamstrings					
	Injured group	Uninjured group	Р	ES	Injured group	Uninjured group	Р	ES		
+180	0.03 (-0.01 to 0.07)	-0.01 (-0.05 to 0.02)	0.0919	a	0.03 (-0.01 to 0.06)	0.00 (-0.08 to 0.07)	0.4070	a		
+60	0.04 (-0.07 to 0.15)	-0.03 (-0.11 to 0.06)	0.3271	0.41	0.05 (-0.10 to 0.21)	-0.04 (-0.17 to0.10)	0.3661	0.36		
-60	0.13 (0.05 to 0.22)	0.01 (-0.09 to 0.11)	0.0542	0.74	0.07 (-0.06 to 0.20)	-0.03 (-0.15 to 0.09)	0.2395	0.46		
-180	0.13 (0.07 to 0.19)	-0.02 (-0.15 to 0.12)	0.0473*	0.82	0.09 (-0.04 to 0.21)	-0.03 (-0.13 to 0.07)	0.1210	0.61		
	Median power frequency									

		Biceps femoris				Medial hamstrings			
	Injured group	Uninjured group	Р	ES	Injured group	Uninjured group	Р	ES	
+180	3.00 (-1.86 to 7.85)	0.74 (-3.55 to 5.04)	0.4570	0.29	3.40 (-4.04 to 10.84)	2.80 (-5.71 to 11.30)	0.9078	0.04	
+60	1.81 (-3.21 to 6.84)	-0.12 (-3.24 to 3.00)	0.4835	0.37	4.08 (-4.75 to 12.90)	3.16 (-1.94 to 8.26)	0.8462	0.08	
-60	2.15 (-4.72 to 9.01)	-0.13 (-3.02 to 2.75)	0.5122	0.27	3.18 (-9.44 to 15.80)	3.82 (-5.93 to 13.57)	0.9315	-0.03	
-180	4.99 (-3.18 to 13.15)	-1.83 (-7.26 to 3.59)	0.1442	0.60	5.76 (-9.63 to 21.14)	-0.84 (-10.52 to 8.85)	0.4377	0.31	

522 Negative movement velocities are indicative of eccentric contractions and positive velocities indicate concentric contractions. Data are presented as mean

523 differences (95% confidence intervals). *Significance was set at p < 0.05. Cohen's d was used to calculate effect size (ES). ^aES for electromyographical

524 activity could not be calculated given the use of this data in the normalisation process.

525 FIGURE LEGENDS

Figure 1: Knee flexor average peak torque at four different isokinetic velocities from the A) injured athletes and B) uninjured athletes. Negative movement velocities are indicative of eccentric contractions and positive velocities indicate concentric contractions. Error bars display standard deviation. * p < 0.0125 injured vs uninjured limbs.

Figure 2: Biceps femoris long head normalised surface electromyography (sEMG) at four different isokinetic velocities from the A) injured athletes and B) uninjured athletes. Negative movement velocities are indicative of eccentric contractions and positive velocities indicate concentric contractions. Error bars display standard deviation.* p < 0.0125 injured vs

534 uninjured limbs.

Figure 3: Medial hamstring normalised surface electromyography (sEMG) at four different

isokinetic velocities from the A) injured athletes and B) uninjured athletes. Negative

537 movement velocities are indicative of eccentric contractions and positive velocities indicate

538 concentric contractions. Error bars display standard deviation.







