

1 **Title:**

2 An evidence-based framework for strengthening exercises to prevent hamstring injury.

3 **Running Title:** Strengthening exercises to prevent hamstring injury.

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31 **Abstract**

32

33 Strength training is a valuable component of hamstring strain injury prevention programmes.

34 However, in recent years a significant body of work has emerged to suggest that the acute
35 responses and chronic adaptations to training with different exercises are heterogeneous.

36 Unfortunately, these research findings do not appear to have uniformly influenced clinical
37 guidelines for exercise selection in hamstring injury prevention or rehabilitation programmes.

38 The purpose of this review is to provide the practitioner with an evidence-base from which to
39 prescribe strengthening exercises to mitigate the risk of hamstring injury. Several studies have

40 established that eccentric knee flexor conditioning reduces the risk of hamstring strain when
41 compliance is adequate. The benefits of this type of training are likely to be at least partly

42 mediated by increases in biceps femoris long head fascicle length and improvements in
43 eccentric knee flexor strength. Therefore, selecting exercises with a proven benefit on these

44 variables should form the basis of effective injury prevention protocols. In addition, a growing
45 body of work suggests that the patterns of hamstring muscle activation diverge significantly

46 between different exercises. Typically, relatively higher levels of biceps femoris long head and
47 semimembranosus activity have been observed during hip-extension oriented movements

48 whereas preferential semitendinosus and biceps femoris short head activation have been
49 reported during knee-flexion oriented movements. These findings may have implications for

50 targeting specific muscles in injury prevention programmes. An evidence-based approach to
51 strength training for the prevention of hamstring strain injury should consider the impact of

52 exercise selection on muscle activation, and the effect of training interventions on hamstring
53 muscle architecture, morphology and function. Most importantly, practitioners should consider

54 the effect of a strength training programme on known or proposed risk factors for hamstring
55 injury.

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64 **Key Points:**

- 65 • A number of prospective studies have established that eccentric knee flexor conditioning
66 reduces the risk of hamstring strain injury when compliance is adequate. These benefits are
67 likely to be at least partly mediated by increases in biceps femoris long head fascicle length,
68 possibly a rightward shift in the angle of peak knee flexor torque, and improvements in
69 eccentric knee flexor strength, although other adaptations may also contribute
- 70 • A large body of evidence suggests that the acute responses and chronic adaptations to
71 training with different hamstring exercises are heterogeneous. Muscle activation may be an
72 important determinant of training-induced hypertrophy, however, contraction mode
73 appears to be the largest driver of architectural changes within the hamstrings.

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75 **1. Introduction**

76

77 Hamstring strain injury is the most common cause of lost training and playing time in running-
78 based sports[1]. In professional soccer, for example, roughly 1 in 5 players will suffer a
79 hamstring injury in any given season [2], and upwards of 20% of these will re-occur [3]. Each
80 injury will typically result in ~17 days lost from training and competition [2], which not only
81 diminishes performance [4], but is also estimated to cost elite soccer clubs as much as ~€280
82 000 per injury [5].

83 It has been argued that most hamstring strains occur during the late swing phase of high speed
84 running and approximately 4 in every 5 affect the long head of biceps femoris [6-8]. While the
85 aetiology of hamstring injury is multifactorial, hamstring strengthening is an important
86 component of injury prevention practices [9-11] and one that has been the focus of a significant
87 amount of research in recent years [12-17]. Large-scale interventions employing the Nordic
88 hamstring exercise have reported 50-70% reductions in hamstring injuries in sub-elite soccer
89 when athletes are compliant [12, 15-17]. Furthermore, hamstring rehabilitation protocols
90 employing long length exercises have proven significantly more effective than conventional
91 exercises in accelerating time to return to play from injury [13, 14]. However, despite these
92 observations, compliance with evidence-based injury prevention protocols is poor [18] and
93 longitudinal data [2, 19-22] suggest that hamstring injury rates have not declined over the past
94 decade in elite soccer and Australian Football. These data highlight the need to improve
95 hamstring injury prevention or risk mitigation practices.

96 In recent years, a growing body of work has emerged highlighting the heterogeneity of
97 hamstring activation patterns in different tasks [23-28] and the non-uniformity of muscle
98 adaptations to different exercises [29-31]. However, this research does not appear to have
99 influenced clinical guidelines for exercise selection in hamstring injury prevention [32, 33] or
100 rehabilitation programmes [34, 35]. An improved understanding of this empirical work may
101 enable practitioners to make better informed decisions regarding exercise selection for the
102 prevention or treatment of hamstring injury. Therefore, the purpose of this review is to provide
103 an evidence based framework for strengthening exercises to prevent hamstring strain injury.
104 The review will aim to discuss 1) the role of strength as a risk factor for hamstring injury; 2)
105 the evidence for strengthening interventions in the prevention or rehabilitation of hamstring
106 injury; 3) the acute patterns of hamstring muscle activation in different exercises; and 4) the
107 malleability of hamstring muscle architecture, morphology and function to targeted strength

108 training interventions. The review will conclude by discussing the implications of this evidence
109 for hamstring injury prevention practices, with particular emphasis on the impact of these
110 variables on known or proposed risk factors for hamstring injury.

111 **2. Literature search**

112

113 The articles included in this review were obtained via searches of Scopus and PubMed from
114 database inception to May 2017 (see Electronic Supplementary Material Appendix S1 for
115 search keywords). A retrospective, citation-based methodology was applied to identify English
116 language literature relating to 1) strength as a risk factor for hamstring injury; 2) the outcomes
117 of prospective strength training interventions on hamstring injury rates; 3) hamstring muscle
118 activation during strengthening exercise(s) in individuals with no history of injury; and 4) the
119 structural or functional adaptations to a period of hamstring strength training. Full text journal
120 publications were the primary source, however published conference abstracts and theses were
121 also included if they satisfied the search criteria.

122 **3. Strength as risk factor for hamstring injury**

123

124 Strength training for the prevention of hamstring injury has been popularised on the basis of
125 the long-held assumption that stronger muscles are more resistant to strain injury [36]. While
126 this may be intuitively appealing, particularly when considering that weakly activated rabbit
127 muscles absorb less energy before failure than fully activated muscles [37], evidence from
128 prospective studies is mixed [38-46]. Although the majority of these studies employed
129 isokinetic dynamometry as their chosen testing methodology [38, 40, 42, 46, 47], more recent
130 field-based measures of eccentric knee flexor strength have also proven reliable [48] and have
131 indicated a level of risk associated with poor eccentric strength [43, 44, 48].

132 ***3.1 Isokinetic dynamometry***

133 In the largest isokinetic investigation, involving 190 hamstring injuries in 614 elite Qatari
134 soccer players, van Dyk and colleagues [42] reported that lower levels of eccentric knee flexor
135 strength significantly elevated the risk of future hamstring injury (odds ratio = 1.37; 95% CI,
136 1.01 to 1.85), albeit with a small effect size (Cohen's $d < 0.2$). In contrast, earlier work by
137 Croisier and colleagues [46] which included 35 injuries in 462 Belgian, Brazilian and French
138 professional soccer players, suggested that athletes with isokinetically derived 'strength
139 imbalances' were 5-fold (relative risk 95% CI = 2.01 to 10.8) more likely to suffer severe (>30

140 days lost) injuries than those without imbalances. In this study [46], correcting these isokinetic
141 parameters via strength training reduced the risk of hamstring injury to the same level as those
142 players without imbalances (relative risk = 1.43; 95% CI = 0.44 to 4.71). However, the results
143 from Croisier and colleagues should be interpreted with caution; firstly, isokinetic testing was
144 conducted at a number of different sites, using different equipment and various arbitrary cut-
145 points, which may have confounded results. Further, the median time to return to sport from
146 hamstring strain is typically less than 30 days [6-8], so it is likely that players in the control
147 group of this study also experienced a significant number of less severe injuries, and this was
148 not accounted for in the analysis. Nevertheless, in a separate study, involving 57 hamstring
149 injuries in 136 professional soccer players, Dauty and colleagues [49] reported that the same
150 isokinetic ‘strength imbalances’ used by Croisier and colleagues, were able to predict
151 approximately 1 in 3 hamstring injuries in the following season and the predictive ability of
152 this testing improved when athletes had multiple imbalances. Fousekis and colleagues [40]
153 have also provided data to suggest that between-limb imbalances in isokinetic eccentric knee
154 flexor torque $\geq 15\%$ increased the risk of hamstring injury 4-fold (95% CI = 1.13 to 13.23) in
155 elite soccer players. Further, in a prospective investigation involving 6 hamstring injuries in 30
156 elite Japanese sprinters, Sugiura and colleagues [41] observed that subsequently injured limbs
157 displayed significant deficits in eccentric knee flexor (95% CI = 0.04 to 0.37 Nm/kg) and
158 concentric hip extensor (95% CI = 0.19 to 0.50 Nm/kg) strength when tested in the preceding
159 12 months. In addition, in a small study involving 6 hamstring injuries in 20 elite Australian
160 Football players, Cameron and colleagues [50] observed that a concentric hamstring to
161 quadriceps ratio of < 0.66 significantly increased the risk of hamstring strain over the following
162 2 years. Lastly, in a prospective study of 6 injuries in 37 elite Australian Football players,
163 Orchard and colleagues [51] observed that subsequently injured limbs displayed significantly
164 lower concentric isokinetic knee flexor strength than uninjured limbs when tested during the
165 pre-season period.

166

167 Despite the aforementioned observations, some studies have failed to identify any association
168 between isokinetic knee flexor strength and hamstring injury risk. In an investigation by
169 Bennell and colleagues [38], involving 9 injuries in 102 elite Australian Football players, no
170 relationship was observed between concentric or eccentric isokinetic knee flexor strength and
171 the likelihood of hamstring injury. However, this study [38] was underpowered to detect small
172 to moderate effects between subsequently injured and uninjured athletes, such as those
173 identified by van Dyk and colleagues [42]. A larger-scale investigation involving 1252

174 collegiate athletes at the National Football League Scouting Combine observed that
175 isokinetically-derived measures of concentric knee flexor strength were not associated with
176 hamstring injury risk in the following competitive season [52]. However, like Croisier and
177 colleague's earlier investigation [46], this study did not employ a standardised testing
178 procedure and strength testing was conducted by different practitioners across a number of
179 sites; therefore it is unclear what effect this may have had on the reliability of these different
180 datasets.

181 ***3.2 Field-based measures***

182 Field-based measures of eccentric knee flexor strength may also be effective for identifying
183 athletes at risk of a future hamstring strain [43, 44]. In a prospective investigation involving 28
184 injuries in 210 Australian Football players, those with lower levels of eccentric knee flexor
185 strength (<279 N) during the Nordic hamstring exercise were 4.3 times (relative risk 95% CI
186 = 1.7 to 11.0) more likely to suffer a hamstring injury in the following season than their stronger
187 counterparts [43]. These findings were supported in a subsequent study [44] involving 27
188 hamstring injuries in 152 professional soccer players, which reported that athletes with lower
189 levels of eccentric knee flexor strength (<337 N) were 4.4 times (relative risk 95% CI = 1.1 to
190 17.5) more likely to sustain a hamstring injury than stronger athletes. In both of these
191 investigations [43, 44], a 10 N increase in strength across the sampled athletes was associated
192 with a 9% smaller risk of future hamstring strain injury. It should also be acknowledged that
193 interactions were observed between eccentric knee flexor strength, age and previous hamstring
194 injury, whereby higher levels of eccentric strength were able to ameliorate the risk of injury
195 associated with being older or having a history of hamstring injury. Nevertheless, a similarly
196 designed study, involving 20 hamstring injuries in 198 amateur and professional rugby players
197 [45], failed to identify an association between eccentric knee flexor strength and hamstring
198 injury. However, in this study, side-to-side imbalances in eccentric strength of $\geq 15\%$ and $\geq 20\%$
199 increased the risk of hamstring injury by 2.4-fold (95% CI = 1.1 to 5.5) and 3.4-fold (95% CI
200 = 1.5 to 7.6), respectively. Lastly, in a prospective investigation involving 8 first-time
201 hamstring injuries in 102 physical education students [53], lower levels of absolute eccentric
202 hamstring strength and a higher isometric to eccentric strength ratio, as measured via hand-
203 held dynamometry, significantly elevated the risk of subsequent hamstring strain.

204 **4. Does strength training protect against hamstring strain injury and re-injury?**

205

206 Over the past decade, a number of prospective studies have established that strength training,
207 particularly when performed with an eccentric bias or at long muscle lengths, reduces the risk
208 of hamstring injury, as long as compliance is high [12-17]. In the first of these studies, Askling
209 and colleagues [54] administered a 10 week YoYo flywheel (a leg curl device which provides
210 eccentric overload) training programme to 15 (from a total pool of 30) elite Swedish soccer
211 players. Across the subsequent season, players in the intervention group experienced
212 significantly fewer (3/15) hamstring strains than those in the control group (10/15). A number
213 of subsequent randomised controlled trials employing the Nordic hamstring exercise have also
214 reported benefits from eccentric conditioning, but only when compliance is adequate [12, 15-
215 17] In the largest of these studies, Petersen and colleagues [15] assigned a 10 week Nordic
216 hamstring programme [55] to 461 of 942 sub-elite Danish soccer players who were
217 subsequently tracked for injury across a single season. Players in the intervention group
218 experienced 71% fewer first-time and 85% fewer recurrent hamstring injuries than players in
219 the control group. However, it should be noted that athletes in this study [55] had no known
220 history of strength training. More recent work by van der Horst and colleagues [17] allocated
221 292 of 597 sub-elite Dutch soccer players to a similar 13 week Nordic hamstring strengthening
222 programme and reported that players who completed the training experienced 69% fewer
223 hamstring strains than those who did not (odds ratio = 0.3, 95% CI = 0.1 to 0.7). Furthermore,
224 Arnason and colleagues [12] reported that Icelandic and Norwegian soccer teams that
225 completed a progressive intensity Nordic exercise programme in pre-season (and a lower
226 volume of the exercise during the competitive season), experienced 65% fewer hamstring
227 strains than those that did not (relative risk = 0.35, 95% CI = 0.2 to 0.6). One limitation of these
228 Scandinavian studies is that they only involved amateur soccer players and consequently it
229 might be argued that they are not applicable to more elite levels of competition. However, in a
230 non-randomised trial, Seagrave and colleagues [16] have recently shown that among 243
231 professional baseball players from a single Major League baseball organisation, those who
232 completed the Nordic hamstring exercise as a part of their team training did not suffer a single
233 hamstring injury throughout the season. In contrast, 9% of athletes who did not complete the
234 exercise missed matches due to hamstring injury.

235 It should be acknowledged that two prospective studies employing the Nordic hamstring
236 exercise, both with very low rates of player compliance, have found no significant effect on
237 hamstring injury rates [47, 56]. In the first of these studies, Engebretsen and colleagues [56]

238 allocated 85 of 161 elite to sub-elite Norwegian soccer players at 'high risk' of hamstring injury
239 to a 10-week Nordic hamstring protocol [55] and reported no benefit of this intervention on
240 injury rates (relative risk = 1.6; 95% CI = 0.8 to 2.9); however, only 1 in 5 players in the
241 intervention group completed the programme [56]. In a subsequent study by Gabbe and
242 colleagues [47], 114 of 220 amateur Australian Football players were asked to complete 5 high
243 volume sessions (~72 repetitions each) of the Nordic hamstring exercise across a 12 week
244 period. This study also reported no benefit of eccentric conditioning on hamstring injury risk
245 (relative risk = 1.2, 95% CI = 0.5 to 2.8); however, only 47% of players completed two training
246 sessions and < 10% completed all five. Those players in the intervention who participated in at
247 least the first two sessions suffered fewer injuries than the control group (4% versus 13%) but
248 this small effect was not statistically significant (relative risk = 0.3, 95% CI = 0.1 to 1.4).

249 Rehabilitation studies employing strengthening exercises at long hamstring muscle lengths
250 have also proven effective in reducing re-injury rates and accelerating time to return to sport
251 [13, 14]. In two separate randomised controlled trials, Askling and colleagues compared a
252 rehabilitation protocol ('L' protocol) emphasising long length hip extension-oriented
253 movements (extender, glider, diver) to a conventional ('C' protocol group) consisting of a
254 contract-relax stretch, a supine bridge and cable pulley exercise performed at shorter hamstring
255 lengths. Elite track and field athletes [13] and professional soccer players [14] who completed
256 the L-protocol experienced a faster return to sport (mean = 28-49 days versus 51-86 days) and
257 no injury recurrences compared to the C-protocol that experienced three. More recently, Tyler
258 and colleagues [57] reported that a progressive criteria-based rehabilitation protocol
259 emphasising eccentric exercises at long hamstring muscle lengths was particularly effective in
260 reducing injury recurrence. Of the 50 athletes who enrolled in the study, those who completed
261 the structured strengthening programme and met return to sport criteria (n=42) remained injury
262 free 23±13 months after a return to sport, whereas 4 athletes who were non-compliant with the
263 exercise programme suffered a re-injury in the following 3-12 months [57].

264 The aforementioned findings provide compelling evidence for the protective role of eccentric
265 only or eccentrically biased strength training against first time and recurrent hamstring injury,
266 but only when compliance is adequate [12-17, 57]. However, most of these studies only
267 explored the injury preventive benefits of a single exercise [12, 15-17, 54] in individuals with
268 no history or unknown histories of strength training, which has limited application to sporting
269 or clinical environments where a combination of exercises are typically employed. An
270 improved understanding of the acute responses and chronic adaptations to various exercises

271 may enable clinicians to make better informed decisions when designing strengthening
272 programmes for the prevention of hamstring injury.

273 **5. Impact of exercise selection on hamstring muscle activation**

274

275 Skeletal muscle activation has the potential to influence the functional and structural
276 adaptations to resistance training [29, 58, 59] and there is a growing body of work to suggest
277 that the hamstrings are activated heterogeneously during a range of different exercises [24-28,
278 60, 61]. Most of these studies have employed either surface electromyography (sEMG) or
279 functional magnetic resonance imaging (fMRI) to map the acute electrical or metabolic activity
280 of the hamstrings during different tasks. The purpose of this section is to provide an overview
281 of the techniques that have been used to assess hamstring activation, highlight the key
282 methodological considerations when interpreting these data, and summarise the available
283 evidence as it relates to the impact of exercise selection on hamstring muscle activation.

284 **5.1. Methods for assessing hamstring muscle activation**

285

286 ***5.1.1. Surface electromyography (sEMG)***

287

288 Surface EMG has been used extensively in the analysis of hamstring exercises [27, 28, 60, 61].
289 This method utilises electrodes, which are placed on the skin overlying the target muscle, to
290 measure the electrical activity generated by active motor units. The EMG amplitude recorded
291 during an exercise is typically expressed relative to the highest level of activation achieved
292 during a maximal voluntary contraction (MVC) [62]. This provides an estimate of voluntary
293 activation (which includes both motor unit recruitment and firing rates) for assessed muscles
294 involved during exercise, with high temporal resolution. However, the coefficient of variation
295 for repeated sEMG measurements has been reported to be as high as 23% [63]. One major
296 limitation of sEMG is its susceptibility to cross talk from neighbouring muscles [62]. As a
297 consequence, it is not possible to reliably discriminate between closely approximated muscles
298 or segments of muscles [64] such as the long and short heads of biceps femoris or either of the
299 medial hamstrings (semimembranosus and semitendinosus) [23]. Surface EMG amplitude is
300 also influenced by the amount of subcutaneous tissue [62], motor unit conduction velocities
301 [65], and the degree to which motor unit firing is synchronous [66]. Furthermore, interpretation
302 of EMG studies is often confounded by inconsistent testing procedures. For example, it is rare
303 to find two studies that have employed the same normalisation technique, and electrode
304 placement is rarely described in adequate detail. Furthermore, some studies differentiate EMG

305 amplitudes between contraction modes [23, 27], whereas others do not [60, 67], which makes
306 comparison difficult (i.e., concentric actions produce higher EMG than eccentric actions at the
307 same load [62]). Nevertheless, appropriately designed and methodologically vigorous studies
308 that minimise the aforementioned limitations can yield valuable information on the extent and
309 patterns of muscle activation during various exercises.

310 ***5.1.2. Functional magnetic resonance imaging (fMRI)***

311
312 The use of fMRI to estimate muscle activation in exercise has become increasingly popular
313 [23-28] since first described by Fleckenstein in 1988 [68]. This technique is based on the
314 premise that muscle activation is associated with a transient increase in the transverse (T2)
315 relaxation time of tissue water, which can be measured from signal intensity changes in fMRI
316 images. These T2 shifts, which increase in proportion to exercise intensity [68, 69], can be
317 mapped in cross-sectional images of muscles and therefore provide exceptional spatial clarity
318 [64, 70]. However, because acute T2 shifts are sensitive to glycolysis [71], and concentric work
319 is markedly less efficient than eccentric work against the same loads [72], it is not sensible to
320 compare the magnitude of T2 shifts between contraction modes, although this has been done
321 previously [73]. Similarly, the extent to which T2 relaxation time increases during exercise can
322 be influenced by muscle fibre composition, metabolic capacity [74] and the vascular dynamics
323 of the active tissue [75], and these factors are likely to differ between individuals. It is therefore
324 inappropriate to compare the absolute magnitude of T2 shifts between individuals because a
325 larger increase in T2 for one subject over another cannot be interpreted as more effective
326 activation. Instead, analytical techniques that compare relative changes in T2 within individuals
327 appear most appropriate and can provide important information on the patterns of muscle use
328 employed in different tasks.

329 ***5.1.3 Factors to consider when interpreting sEMG and fMRI***

330
331 Given the methodological complexities of sEMG and fMRI, there are some additional factors
332 that should be considered when interpreting data from these studies. Firstly, because both EMG
333 [62] and T2 relaxation times [69] increase in proportion to exercise intensity, greater loads will
334 typically result in higher levels of ‘activation’ than lower loads for any given exercise.
335 Therefore, when comparing different exercises it is important to consider the relative intensity
336 of each task. In addition, when comparing the ‘patterns’ of muscle activation between exercises
337 it is important to consider that the ratio of lateral to medial (or biceps femoris long head to
338 semitendinosus) ‘activation’ is calculated independently of the magnitude of sEMG or T2

339 relaxation time increase. It is possible that some exercises may elicit selective activation of a
340 desired structure, but the extent of activation may still be insufficient to stimulate positive
341 adaptations.

342

343 **5.2. Hamstring muscle activation during specific exercises**

344

345 ***5.2.1. Magnitude of hamstring muscle activation***

346

347 Studies employing sEMG have shown that the magnitude of hamstring muscle activation is
348 variable between exercises. During eccentric-only movements, very high levels of biceps
349 femoris (72-91% MVC) and medial hamstring normalised EMG (nEMG) (82-102% MVC)
350 have consistently been observed during the Nordic hamstring exercise [23, 60, 76]. Most other
351 studies have not differentiated between contraction modes and instead report mean values
352 across the entire movement. Very high levels of biceps femoris and medial hamstring nEMG
353 (>80% MVC) have been reported for supine sliding bodyweight leg curls [60, 67], seated and
354 prone leg curls [60, 77], loaded and unloaded hip extension [60], kettlebell swings [60], and a
355 supine straight leg bridge [23, 60, 67].

356 ***5.2.2. Patterns of hamstring muscle activation***

357

358 Several sEMG studies have attempted to characterise the patterns of individual hamstring
359 muscle activation during different strengthening exercises. A recent study [23] reported more
360 selective biceps femoris nEMG activity in eccentric and concentric actions during the 45⁰ hip
361 extension and hip hinge exercises. In contrast, the same study observed more selective nEMG
362 of the medial hamstrings during an eccentric and concentric leg curl and the Nordic hamstring
363 exercise, despite the latter demonstrating the highest absolute levels of biceps femoris nEMG
364 of any exercise. This is in line with earlier work by Ono and colleagues [28] who observed
365 more selective nEMG of the biceps femoris and semimembranosus relative to the
366 semitendinosus during the eccentric and concentric phases of a stiff leg deadlift. In contrast,
367 during a supramaximal eccentric-only leg curl, the same authors [27] observed with sEMG that
368 the semitendinosus was significantly more active than the semimembranosus and trended
369 towards being more active than the biceps femoris. In support of these findings, McAllister and
370 colleagues [78] reported significantly more biceps femoris nEMG during an eccentric
371 Romanian deadlift than an eccentric prone leg curl and eccentric glute-ham-raise, and
372 significantly more biceps femoris nEMG during an eccentric good morning squat than a prone
373 leg curl. However, other authors have found conflicting results. For example, Zebis and

374 colleagues [60] observed higher levels of semitendinosus than biceps femoris nEMG during a
375 kettlebell swing and Romanian deadlift, and higher levels of biceps femoris than
376 semitendinosus nEMG during a supine leg curl and hip extension exercise. Furthermore,
377 Tsaklis and colleagues [67] observed preferential recruitment of the biceps femoris during
378 ‘fitball’ flexion, and selective nEMG activity of the semitendinosus during a lunge, kettlebell
379 swing and single leg Romanian deadlift. However, these two previous studies [60, 67] did not
380 report sEMG for each contraction mode, which may at least partly explain the divergent results.

381 Studies using fMRI are generally consistent with the results of sEMG investigations; however,
382 the increased spatial clarity of this technique allows for inferences to be drawn on the relative
383 metabolic activity of each hamstring muscle belly (Figure 1). Early work by Ono and
384 colleagues [27] revealed that the semitendinosus is selectively activated during the eccentric
385 prone leg curl, while the semimembranosus and biceps femoris are preferentially recruited
386 during the stiff leg deadlift [28]. More recent observations have provided evidence that the
387 semitendinosus is preferentially recruited during the Nordic hamstring exercise [23, 24, 26, 73,
388 79], and a prone leg curl [25]. In contrast, the biceps femoris long head and other biarticular
389 hamstrings appear to be more active during a 45° hip extension exercise than the Nordic
390 exercise [23]. In addition, the long head of biceps femoris appears to be significantly more
391 active than its short head during a single leg supine bridge exercise [80]. Further, Mendiguchia
392 and colleagues have observed elevated T2 values in the proximal but not middle or distal
393 portions of biceps femoris long head after a lunge exercise [25]. Figure 1 illustrates the ratio of
394 biceps femoris long head to semitendinosus activity (as determined via exercise-induced T2
395 relaxation time shifts) during all studies that have reported these data. Ratios > 1.0 indicate
396 higher levels of biceps femoris long head than semitendinosus activity.

397

398

399

INSERT FIGURE 1

400 **Figure 1.** Ratio of BFLH to ST percentage change in T2 relaxation time from different
401 exercises. Ratios > 1.0 indicate higher levels of BFLH than ST activity. Note the trend for
402 relatively higher levels of BFLH activity during hip extension-oriented movements and more
403 selective ST activity during knee flexion-oriented movements. BFLH, biceps femoris long
404 head; BW, bodyweight; RM, repetition maximum; ST, semitendinosus; T2, transverse
405 relaxation time.

406

407

408 Collectively, the abovementioned findings suggest that the magnitude and patterns of muscle
409 activation are heterogeneous between different exercises. While the results of sEMG
410 investigations are variable, the improved spatial clarity of fMRI suggests that knee flexion-
411 oriented movements (i.e., Nordic hamstring exercise, leg curl) appear to selectively activate
412 the semitendinosus, whereas movements involving a significant amount of hip extension (i.e.,
413 stiff leg deadlift) appear to more heavily activate the biceps femoris long head and
414 semimembranosus (Figure 1). Importantly, these patterns of preferential activation have
415 recently been shown to match the patterns of hamstring muscle hypertrophy after 10 weeks of
416 training [29], as discussed in section 6.2.

417

418 **5.3. Hamstring muscle damage following specific exercises**

419

420 In addition to the acute T2 response to exercise, unaccustomed eccentric exercise can be
421 associated with a delayed T2 increase which parallels indices of muscle damage [70]. This
422 prolonged T2 increase is thought to arise as a consequence of oedema [81], and can therefore
423 persist for days to weeks after exposure to unaccustomed exercise involving eccentric muscle
424 actions [82]. In one of the few studies to have assessed this parameter in the hamstrings, Kubota
425 and colleagues [83] demonstrated that 50 repetitions of an eccentric leg curl exercise performed
426 at 120% 1-repetition maximum (1RM) resulted in an elevated T2 value for the semitendinosus,
427 but not the biceps femoris long head or semimembranosus, 72 hours after exercise. Similar
428 results were reported by Mendiguchia and colleagues [25] who observed an increased T2 value
429 for the semitendinosus, but not the biceps femoris or semimembranosus, 48 hours after 18
430 repetitions of an eccentric leg curl exercise. Subsequent work [26] reported that 40 repetitions
431 of the supramaximal Nordic hamstring exercise resulted in an elevated T2 value for the distal
432 portion of biceps femoris short head for up to 72 hours after exercise; however, no changes
433 were observed for any of the other hamstrings. Lastly, Ono and colleagues [28] observed a
434 significant increase in T2 for the semimembranosus 72 hours after 50 repetitions of
435 submaximal (60% 1RM) hip extension exercise. Collectively, these observations suggest that
436 unaccustomed eccentrically biased exercise is likely to result in some damage to the trained
437 muscles particularly when the intensity is supramaximal (i.e., $\geq 1\text{RM}$ loads), and the
438 distribution of that damage appears to be closely related to the acute T2 shifts observed

439 immediately after exercise (Figure 1). These findings may have implications for the structural
440 adaptations experienced from training, which should be a focus of future work.

441 **6. Architectural, morphological and performance-based adaptations to different** 442 **exercises**

443
444 The adaptability of hamstring structure and function in response to various training
445 interventions may have important implications for strategies aimed at preventing hamstring
446 injury. It is particularly relevant to consider the effect of various exercises on known or
447 proposed risk factors for hamstring strain injury, such as biceps femoris long head fascicle
448 length [44] and eccentric knee flexor strength [42-44, 46]. This section aims to describe the
449 results of training studies that have explored the architectural, morphological or functional
450 adaptations to a period of hamstring conditioning, while also providing a rationale for why
451 certain adaptations are considered favourable in the context of mitigating the risk of hamstring
452 injury.

453 **6.1. Biceps femoris long head fascicle length**

454
455 Recent evidence suggests that professional soccer players with shorter biceps femoris long
456 head fascicles (<10.56cm) were 4.1-times more likely to sustain a future hamstring strain injury
457 than those with longer fascicles and that the probability of injury was reduced by ~21% for
458 every 1cm increase in fascicle length (Figure 2) [44]. Retrospective evidence also suggests that
459 previously injured biceps femoris long head muscles display significantly shorter fascicles than
460 muscles without a history of injury [84]. While the mechanism(s) by which shorter fascicles
461 predispose an individual to strain injury is not fully understood, it is hypothesised that shorter
462 fascicles, with fewer sarcomeres in series, will be more susceptible to damage as a consequence
463 of sarcomere “popping”, while actively lengthening on the descending limb of the force-length
464 curve [85]. Therefore, fascicle lengthening is thought to be at least partly mediated by the
465 addition of in-series sarcomeres which would serve to reduce the over-lengthening of those
466 sarcomeres during subsequent eccentric exercise [86].

467

468

INSERT FIGURE 2

469 **Figure 2.** Pre-season biceps femoris long head fascicle length (y axis) and eccentric knee flexor
470 (Nordic) strength (x axis) values for professional soccer players who did (red dots) and did not
471 (green dots) suffer a hamstring strain injury in the subsequent competitive season. Dotted lines

472 indicate receiver-operator curve derived cut points for each variable; players with short biceps
473 femoris long head fascicles ($< 10.56\text{cm}$) and low eccentric strength ($< 337\text{ N}$) were 4.1 and 4.4
474 times, respectively, more likely to suffer a future hamstring strain injury than those with longer
475 fascicles or higher levels of strength [44].

476

477 Biceps femoris long head fascicle length has been shown to increase following eccentric but
478 not concentrically biased resistance training (Table 1). Potier and colleagues [31] observed a
479 34% increase in biceps femoris long head fascicle length following 8 weeks of eccentric leg
480 curl exercise. Further, Timmins and colleagues [30] reported a 16% increase in biceps femoris
481 long head fascicle length after 6 weeks of eccentric training on an isokinetic dynamometer. In
482 the same study, the authors also noted that long length concentric training on the same device
483 resulted in a 12% reduction in biceps femoris long head fascicle length [30] Similarly,
484 concentric only leg curl training has been reported to result in a 6% shortening of biceps femoris
485 long head fascicles [87]. In contrast, both low [88, 89] and high volume [29, 88, 90, 91]
486 programmes employing the eccentric-only Nordic hamstring exercise observed a 13-24%
487 increase in biceps femoris long head fascicle length across a 4-10 week training period (Figure
488 3). Furthermore, 10 weeks of conventional (combined eccentric and concentric contractions)
489 hip extension training at long hamstring lengths resulted in a 13% increase in biceps femoris
490 fascicle length (Figure 3) [29]. Lastly, Guex and colleagues [92] observed a 5% and 9%
491 increase in biceps femoris long head fascicle length after short-length and long-length eccentric
492 training on an isokinetic dynamometer. Only two studies have failed to observe an increase in
493 biceps femoris fascicle length following a period of eccentric conditioning [91, 93]; however,
494 in one of these studies [91], training was performed in a fatigued state and in the other [93] the
495 authors also noted no improvement in eccentric knee flexor strength. These observations
496 suggest the possibility that the intensity of exercise in each of these interventions may not have
497 been sufficiently high to stimulate sarcomerogenesis. Together, these data suggest that
498 concentric and eccentric actions appear to have opposing effects on hamstring architecture and
499 that the combination of contraction modes (as observed in almost every conventional strength
500 training exercise) may somewhat dampen the elongation of biceps femoris long head fascicles.

501 **Table 1.** Strength training interventions studies that have reported architectural changes to the
502 biceps femoris long head.

Study	Exercise	Contraction mode(s)	Peak MTU length	Intensity	Maximum volume (sets*reps / session)	Maximum frequency (sessions / week)	Biceps femoris long head fascicle length
Presland et al. [88]	Nordic	Eccentric	Moderate	Supramax	5*10	2	+ 23%
	Nordic	Eccentric	Moderate	Supramax	4*2	2	+ 24%
Duhig et al. [87]	Nordic	Eccentric	Moderate	Supramax	5*6	2	+ 13%
	Leg curl	Concentric	Moderate	6-8RM	5*6	2	- 6%
Lovell et al. [91]	Nordic (<i>bef</i>)	Eccentric	Moderate	Supramax	4*12	2	+ 12.9%
	Nordic (<i>aft</i>)	Eccentric	Moderate	Supramax	4*12	2	- 2.3%
	Static & side bridge	Isometric	Short	Isometric	3*40sec	2	- 5.4%
Alvares et al. [89]	Nordic	Eccentric	Moderate	Supramax	3*10	2	+ 22%
Alonso-Fernandez et al. [90]	Nordic	Eccentric	Moderate	Supramax	3*10	3	+ 23.9%
Seymore et al. [93]	Nordic	Eccentric	Moderate	Supramax	3*8-12	3	+ 0.0%
Bourne et al. [29]	Nordic	Eccentric	Moderate	Supramax	5*10	2	+ 21%
	Hip extension	Conventional	Long	6-10RM	5*10	2	+ 13.2%
Timmins et al. [30]	Seated isokinetic knee flexion	Eccentric	Long	Maximal	6*8	3	+ 16%
		Concentric	Long	Maximal	6*8	3	- 11.8%
Guex et al.[92]	Seated isokinetic knee flexion	Eccentric	Long	Maximal	5*8	3	+ 9.3%
	Lying isokinetic knee flexion	Eccentric	Short	Maximal	5*8	3	+ 4.9%
Potier et al. [31]	Leg curl	Eccentric	Moderate	1RM	3*8	3	+ 34%

503 MTU, muscle-tendon unit; Supramax, supramaximal; RM, repetition-maximum; *bef*,
504 performed before regular training; *aft*, performed after regular training.

505

506

INSERT FIGURE 3

507 **Figure 3.** Training-induced increases in biceps femoris long head fascicle length (y axis) and
508 eccentric knee flexor (Nordic) strength (x axis) following 6-10 weeks of hip extension training
509 (red dots), or high (blue and green dots) and low volume (purple dots) Nordic hamstring
510 training [29, 88]. The size of each data point indicates the estimated probability of future
511 hamstring strain, based on previously published data in elite soccer players (Figure 2) [44].
512 Note, all individuals experience a reduction in hamstring injury risk as a consequence of the
513 training intervention. HSI, hamstring strain injury.

514

515 **6.2 Myotendinous junction**

516 Recently, it has been proposed that a small proximal biceps femoris long head aponeurosis may
517 be a risk factor for future hamstring strain injury [94]. Although prospective investigations are
518 lacking, computational modelling [95, 96] has demonstrated that biceps femoris aponeurosis
519 geometry has a significant impact on the location and magnitude of strain within this muscle.
520 For example, Rehorn and colleagues [96] reported that an 80% reduction in the width of the
521 proximal biceps femoris long head aponeurosis increased proximal myotendinous junction
522 (MTJ) strains by 60%. Given that running-induced strain injury occurs most commonly at the
523 proximal MTJ of the biceps femoris long head [97], it is plausible that interventions targeted
524 at improving the size of the proximal aponeurosis may confer some injury preventive benefits.
525 Despite this possibility, the authors are not aware of any study to explore training-induced
526 adaptations to the size of this structure. However, Wakahara and colleagues [98] have recently
527 reported that training-induced hypertrophy of the vastus lateralis was correlated with an
528 increase in the width of this muscle's aponeurosis ($r=0.64$), and others have previously shown
529 that weightlifters display larger vastus lateralis aponeuroses than untrained individuals [99].
530 These data suggest the possibility that aponeurosis geometry may increase as a function of
531 muscle hypertrophy; however, further work is required to confirm this hypothesis.

532 In light of evidence that strain magnitudes are greatest in the proximal MTJ of the hamstrings,
533 the composition of this structure and its surrounding fibres is another factor which could,
534 theoretically, influence its susceptibility to damage. Jakobsen and colleagues [100] have
535 recently shown that 4 weeks of knee-flexor strength training involving the Nordic hamstring
536 exercise, leg curls and hip extensions altered collagen expression in the endomysium of muscle
537 fibres at the MTJ junction of the semitendinosus and gracilis. In particular, the authors noted
538 that training increased the amount of collagen XIV, a protein that may be important in
539 strengthening the extracellular matrix and unloading the MTJ [100]. These results suggest that
540 altered collagen expression may be at least one additional mechanism by which strength
541 training protects against hamstring strain injury, and this should be a focus of subsequent
542 investigations. Future work should also seek to determine the effect of exercise selection,
543 contraction mode and training intensity on these adaptations.

544

6.3. Hamstring muscle size

Muscle volume has not been identified as a risk factor for hamstring strain injury. However, previously injured hamstrings have been reported to display significant deficits in muscle size as measured via MRI, despite apparently successful rehabilitation and a return to pre-injury levels of training and competition (Figure 4) [101]. Future work is needed to clarify if these deficits lead to an increased risk of injury; however, the associated cost (~ \$600 AUD per hour for MRI) and time-demands (~4 hours to analyse a single scan) of these types of studies may be a limiting factor. Nevertheless, muscle strength is directly correlated to its anatomical cross sectional area [102], and it therefore seems logical that hypertrophy should be a goal of interventions aimed at improving hamstring strength.

INSERT FIGURE 4

Figure 4. Unpublished observations of biceps femoris long head atrophy and compensatory hypertrophy of its short head 4.5 years following a distal biceps femoris strain injury in a national champion long jump athlete. These data are consistent with earlier findings by Silder and colleagues [101].

To the authors' knowledge, only two studies have explored the hypertrophic adaptations of the hamstrings to strength training. In the first [29], MRI was used to measure hamstring muscle volumes and peak anatomical cross-sectional areas before and after a period of hamstring conditioning. Following 10 weeks of training, hip extension exercise resulted in relatively uniform hypertrophy of the biarticular hamstrings and significantly more growth of the biceps femoris long head than did the Nordic hamstring exercise, which preferentially developed the semitendinosus and the short head of biceps femoris. In a separate investigation, Seymore and colleagues [103] employed panoramic ultrasound to determine the effect of 6 weeks of Nordic hamstring training on biceps femoris long head and semitendinosus volume. In line with the aforementioned MRI observations [29], the semitendinosus experienced twice as much hypertrophy (~20% increase in volume) as the biceps femoris long head (~10% increase in volume). Interestingly, the patterns of muscle hypertrophy experienced by participants in the first of these studies [29] were an almost exact match to the acute T2 changes observed after 50 repetitions of each exercise in a previous study (Figure 5) [23]. These observations match

577 those of earlier work by Wakahara and colleagues [58] who demonstrated that regional
578 differences in triceps brachii activation during elbow extensor exercise, as revealed by fMRI
579 after a single session, predicted regional differences in muscle hypertrophy following 12 weeks
580 of training. This suggests that fMRI studies of the hamstrings may have the potential to identify
581 the exercises that are most effective in stimulating hypertrophic adaptations in the biceps
582 femoris long head (or either of the medial hamstrings), but further work is needed to confirm
583 this hypothesis. It should also be noted that while the Nordic hamstring exercise appears to
584 cause small to moderate acute changes in T2 relaxation times and minimal hypertrophy in the
585 biceps femoris long head, this does not prevent large changes in fascicle lengths from occurring
586 [29].

587

588

INSERT FIGURE 5

589 **Figure 5.** Previously published observations [23, 29] demonstrating similarities between the
590 acute T2 shifts (grey bars) observed after 50 repetitions of the a) Nordic hamstring exercise,
591 and b) hip extension exercise, and the hypertrophic adaptations experienced after 10 weeks of
592 training (black bars). Adapted from Bourne et al. [23] and Bourne et al. [29], with
593 permission. Data are presented as mean \pm SD. BFLH, biceps femoris long head; BFSH
594 biceps femoris short head; ST, semitendinosus; SM, semimembranosus. T2, transverse
595 relaxation time.

596

597 In recent years, two-dimensional ultrasound has proven reliable in assessing measures of mid-
598 muscle belly thickness in the biceps femoris long head [84], and a series of underpowered
599 studies have employed it to examine changes in the size of this muscle following training
600 interventions. However, it should be acknowledged that this technique does not currently allow
601 for inferences to be drawn on the ‘patterns’ of muscle hypertrophy within or between the
602 hamstring muscles. In the first of these studies, Timmins and colleagues [30] reported that 6
603 weeks of concentric or eccentric-only training on an isokinetic dynamometer resulted in non-
604 significant 0.1cm (95% CI = -0.1 to 0.4cm) and 0.2cm (95% CI = -0.1 to 0.5cm) increases in
605 biceps femoris long head thickness, respectively. More recently, Presland and colleagues [88]
606 observed no significant increase in biceps femoris long head thickness after a low (0.1cm, 95%
607 CI = -0.4 to 0.5cm) or high volume (0.1cm, 95% CI = -0.3 to 0.6cm) programme consisting
608 exclusively of the Nordic hamstring exercise. Similarly, Alonso-Fernandez and colleagues [90]

609 noted a ~0.2cm increase in biceps femoris thickness after 9 weeks of Nordic training, while
610 Lovell and colleagues [91] noted a ~0.2cm increase after 12 weeks of training, but only when
611 Nordics were completed in a fatigued state (i.e., after regular soccer training). In contrast,
612 Alvares and colleagues [89] observed no increase in biceps femoris size after 4 weeks of
613 training with the same exercise. Together, these data support the aforementioned MRI [29] and
614 panoramic ultrasound [103] observations in suggesting that the Nordic hamstring exercise may
615 not provide a powerful stimulus for hypertrophy in the biceps femoris long head. However, it
616 is possible that these adaptations may be influenced by the volume of training, or the timing of
617 when that training is completed.

618

619 **6.4. Knee flexor strength**

620

621 Higher levels of eccentric but not concentric knee flexor strength have been shown in most [40,
622 42-44, 46], but not all prospective studies [38, 45], to be associated with a reduced risk of
623 hamstring injury (Figure 2). Therefore, it is of interest to determine the adaptability of eccentric
624 knee flexor strength in response to different training interventions. Askling and colleagues [54]
625 reported a significant 19% increase in isokinetic eccentric knee flexor strength after 10 weeks
626 of eccentric YoYo fly wheel training on a leg curl ergometer. Similarly, Mjolsnes and
627 colleagues [55] reported an 11% increase in eccentric isokinetic knee flexor strength at $-60^{\circ}.s^{-1}$
628 ¹ after 10 weeks of Nordic hamstring exercise training. In the same study [55], athletes who
629 completed concentrically biased leg curl training experienced no improvement in eccentric
630 strength. More recently, Timmins and colleagues [30] reported a 13-17% increase in eccentric
631 isokinetic knee flexor torque at a range of velocities, following 6 weeks of eccentric or
632 concentric only training on the same device. Furthermore, 10 weeks of Nordic hamstring or
633 hip extension training resulted in a 74% and 78% increase in peak eccentric knee flexor force
634 as measured during the Nordic hamstring exercise (Figure 3) [29]. In comparison, two separate
635 studies have shown that a briefer 4 week period of Nordic hamstring training resulted in a
636 ~14% [89] and ~21% [104] increase in peak eccentric knee flexor torque as measured on an
637 isokinetic dynamometer [89], although a similar study failed to observe any increase in this
638 parameter [93]. Only one study has explored the effect of training volume on eccentric knee
639 flexor strength. In this study, Presland and colleagues [88] observed a 30% and 27.5% increase
640 in eccentric knee flexor strength during the Nordic hamstring exercise following 6 weeks of
641 low (8 repetitions per week) or high (up to 100 repetitions per week) volume training,
642 respectively, on the same device (Figure 3). These data suggest the possibility that very low

643 volumes of intense eccentric knee flexor training may be effective in improving eccentric
644 strength, which may have implications for encouraging compliance with hamstring injury
645 prevention programmes [18, 105].

646 Some studies have reported improvements in eccentric knee flexor strength following
647 programmes incorporating several exercises. For example, Guex and colleagues [106]
648 observed a 20-22% improvement in eccentric isokinetic strength at $-30^{\circ} \cdot s^{-1}$ and $-120^{\circ} \cdot s^{-1}$
649 following 6 weeks of eccentric-only leg curls and hip extension exercises (in conjunction with
650 regular sprint training). Further, Holcomb and colleagues [107] observed a significant
651 improvement in eccentric isokinetic knee flexor strength relative to concentric quadriceps
652 strength following 6 weeks of conventional hamstring conditioning including single leg
653 hamstring curls, stiff leg deadlifts, good morning squats, trunk hyperextensions, resisted sled
654 walking and a 'fitball leg curls'. More recently, Mendiguchia and colleagues [108] reported a
655 moderate to large improvement in eccentric knee flexor strength (mean = 13%, $d = 0.66$) after
656 7 weeks of 'neuromuscular training' emphasising eccentric (Nordic hamstring and box drops)
657 and conventional (bilateral and unilateral deadlifts, hip thrusts, lunges) hamstring exercises.

658 **6.5. Angle of peak knee flexor torque**

659
660 A rightward shift in the torque-joint angle relationship of the knee flexors may increase the
661 ability of the hamstrings to generate higher levels of torque at longer muscle lengths. Brockett
662 and colleagues [109] were the first to demonstrate that a single session of 72 repetitions of the
663 Nordic hamstring exercise resulted in a significant $\sim 8^{\circ}$ shift in the angle of peak knee flexor
664 torque towards longer muscle lengths for up to 8 days after training. These findings were
665 supported by Clark and colleagues [110] who reported a $\sim 6.5^{\circ}$ shift after 4 weeks of lower
666 volume Nordic hamstring training, and more recently by Seymore and colleagues [93] who
667 noted a $\sim 3.6^{\circ}$ shift following 6 weeks of training with the same exercise. Brughelli and
668 colleagues [111] also demonstrated that 4 weeks of Nordic hamstring conditioning stimulated
669 a $\sim 2.3^{\circ}$ shift in the angle of peak knee flexor torque toward longer muscle lengths in a group
670 of professional soccer players. However, in this study [111], athletes who completed eccentric
671 box drops, lunge pushes, forward deceleration steps and a 'reverse Nordic' exercise in addition
672 to regular Nordics experienced a significantly greater shift (4°) than those who did not. In a
673 separate multimodal intervention, Kilgallon and colleagues [112] reported that 7 sessions of
674 eccentrically-biased leg curls and stiff leg deadlifts resulted in a $\sim 20^{\circ}$ shift in the angle of peak
675 torque towards a more extended knee angle 4 days after training, while concentrically biased

676 training with the same exercises resulted in a 7⁰ shift towards shorter muscle lengths. Lastly,
677 Guex and colleagues [92] observed a 17.3% shift in the angle of peak knee flexor torque toward
678 longer muscle lengths after long length eccentric training on an isokinetic dynamometer, with
679 no significant change noted after short length training on the same device. Collectively, the
680 aforementioned studies suggest that short periods of hamstring conditioning, employing
681 eccentrically biased or long length exercises, stimulate significant increases in the angle of
682 peak knee flexor torque towards longer muscle lengths. The mechanism(s) underpinning these
683 short-lived adaptations is not fully understood, but it is likely that architectural changes (i.e.,
684 increased fascicle lengths) in the trained muscles are at least partly responsible [86].

685 **6.6. Performance**

686
687 Some of the aforementioned studies have also explored the impact of hamstring strength
688 training on measures of performance. For example, in the study by Askling and colleagues
689 [54], a 2.4% improvement in running speed over 30m was reported after 10 weeks of flywheel
690 leg curl training. Furthermore, 7 weeks of hamstring strength training coupled with plyometric
691 and acceleration training resulted in a small (mean = 1.6%, $d = 0.3$) improvement in 5m but
692 not 20m sprint speed [108]. Lastly, Clark and colleagues [110] noted a significant improvement
693 in vertical jumping height following 8 sessions of Nordic hamstring training.

694 **7. Implications for hamstring injury prevention practices**

695
696 Despite an increased focus on hamstring strength in prophylactic programs, exercise selection
697 is often implemented on the basis of clinical recommendations and assumptions rather than
698 empirical evidence [32-35]. It is often argued that exercises should mimic the load, range of
699 motion and velocities experienced during the presumably injurious terminal-swing phase of
700 sprinting to be effective in reducing injury [32, 33, 106]. While this type of theoretical
701 framework may be conceptually appealing, it neglects to consider what effect, if any, such
702 exercises may have on previously identified risk factors for hamstring injury. It also ignores
703 the fact that the Nordic hamstring exercise, which fulfils almost none of these criteria, has a
704 uniquely strong evidence base for preventing hamstring strain injury [12, 15-17].

705 Over the past decade, a number of prospective studies have established that eccentric knee
706 flexor conditioning reduces the risk of hamstring strain injury [12-17]. The benefits of this form
707 of exercise are likely to be mediated at least partly by increases in biceps femoris long head
708 fascicle length [29, 44], possibly a rightward shift in the angle of peak knee flexor torque [110-

709 112], and improvements in eccentric knee flexor strength (Figure 3) [29, 44]. However,
710 reductions in first-time injuries have only been reported as a consequence of interventions
711 employing the Nordic hamstring exercise [12, 15-17] or an eccentric fly wheel leg curl [54].
712 An improved understanding of the acute and chronic effects of other common hamstring
713 exercises on known or proposed risk factors for hamstring injury is needed to inform the design
714 of intervention studies which may one day prove to be effective in reducing hamstring injury
715 rates.

716 The acute patterns of hamstring muscle activation during different exercises are extremely
717 heterogeneous. Studies employing sEMG are somewhat variable, however those employing
718 fMRI have consistently demonstrated relatively more biceps femoris long head and
719 semimembranosus activity during hip-extension oriented movements (i.e., stiff leg deadlifts),
720 and relatively more semitendinosus and biceps femoris short head activation during knee-
721 flexion oriented movements (i.e., Nordic hamstring exercise and leg curls) (Figure 1). On the
722 basis of these findings, it seems logical to prescribe athletes a combination of both hip and knee
723 dominant movements to effectively target all heads of the hamstrings. However, it remains
724 unclear as to how important the magnitude or patterns of hamstring activation are in stimulating
725 positive adaptations in these muscles. Recent evidence suggests that transient T2 shifts
726 observed after a single bout of exercise may be associated with hypertrophy following a period
727 of training (Figure 5) [29], which suggests the possibility that fMRI may be used to select
728 exercises that target specific muscles or portions of muscles in injury prevention or
729 rehabilitation programmes. However, further work is required to clarify this hypothesis and to
730 determine the impact of muscle activation on the architectural and functional adaptations to a
731 period of training.

732 It should be acknowledged that while the research findings discussed in this review may inform
733 the design of strength training interventions for the prevention of first-time hamstring injury, it
734 remains unknown as to whether they may also be applicable to injury rehabilitation practices.
735 Given evidence of altered hamstring activation [23], architecture [84] and morphology [101],
736 long after a return to sport from hamstring strain, it is possible that previously injured
737 individuals will respond differently to strength training stimuli. Therefore, exploration of the
738 acute responses and chronic adaptations of previously injured hamstrings to common
739 rehabilitation exercises should be a focus of future research.

740 **8. Conclusion**

741

742 While strength training appears to be an effective means of reducing hamstring injury rates,
743 the acute responses and chronic adaptations to training with different exercises are non-
744 uniform. An improved understanding of this empirical evidence may enable practitioners to
745 make better informed decisions around exercise selection for the prevention or treatment of
746 hamstring strain injury. These data may also inform the design of training interventions, which
747 may one day prove effective in reducing hamstring injury rates in sport.

748

749

Compliance with Ethical Standards

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Anthony Shield and David Opar are listed as co-inventors on a patent filed for a field test of eccentric hamstring strength (PCT/AU2012/001041.2012) as well as being shareholders in a company responsible for commercialising the device. Matthew Bourne, Ryan Timmins, Tania Pizzari, Joshua Ruddy, Casey Sims and Morgan Williams declare that they have no conflicts of interest relevant to the content of this review.

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