

1 **TITLE**

2 **Impact of the Nordic hamstring and hip extension exercises on hamstring architecture**  
3 **and morphology: implications for injury prevention**

4  
5 **Authors**

6  
7 Matthew N. Bourne<sup>1,2,3</sup> Steven J. Duhig<sup>1,2</sup>, Ryan G. Timmins<sup>4</sup>, Morgan D. Williams<sup>5</sup>,  
8 David A. Opar<sup>4</sup>, Aiman Al Najjar<sup>6</sup>, Graham K. Kerr<sup>1,2</sup>, Anthony J. Shield<sup>1,2</sup>.

9  
10  
11

12 <sup>1</sup>School of Exercise and Nutrition Science, Faculty of Health, Queensland University of  
13 Technology, Brisbane, Australia.

14 <sup>2</sup> Institute of Health and Biomedical Innovation, Queensland University of Technology,  
15 Brisbane, Australia.

16 <sup>3</sup> Queensland Academy of Sport, Centre of Excellence for Applied Sport Science Research,  
17 Brisbane, Australia.

18 <sup>4</sup>School of Exercise Sciences, Australian Catholic University, Melbourne, Australia.

19 <sup>5</sup>School of Health, Sport and Professional Practice, Faculty of Life Sciences and Education,  
20 University of South Wales, Wales, United Kingdom

21 <sup>6</sup>Centre for Advanced Imaging, University of Queensland, Brisbane, Australia.

22

23 **Corresponding Author**

24 Dr Anthony Shield

25 School of Exercise and Nutrition Sciences and the Institute of Health and Biomedical  
26 Innovation,

27 Queensland University of Technology, Victoria Park Road, Kelvin Grove, 4059,  
28 Brisbane, Queensland, Australia.

29 Email: [aj.shield@qut.edu.au](mailto:aj.shield@qut.edu.au)

30 Ph: +61 7 3138 5829

31 Fax: +61 7 3138 3980

32 **ABSTRACT**

33 The architectural and morphological adaptations of the hamstrings in response to training with  
34 different exercises have not been explored. **PURPOSE:** To evaluate changes in biceps femoris  
35 long head (BF<sub>LH</sub>) fascicle length and hamstring muscle size following 10-weeks of Nordic  
36 hamstring exercise (NHE) or hip extension (HE) training. **METHODS:** Thirty recreationally  
37 active male athletes (age,  $22.0 \pm 3.6$  years, height,  $180.4 \pm 7$  cm, weight,  $80.8 \pm 11.1$  kg) were  
38 allocated to one of three groups: 1) HE training (n=10), NHE training (n=10), or no training  
39 (CON) (n=10). BF<sub>LH</sub> fascicle length was assessed before, during (Week 5) and after the  
40 intervention with 2D-ultrasound. Hamstring muscle size was determined before and after  
41 training via magnetic resonance imaging. **RESULTS:** Compared to *baseline*, BF<sub>LH</sub> fascicles  
42 were lengthened in the NHE and HE groups at *mid-* ( $d = 1.12 - 1.39$ ,  $p < 0.001$ ) and *post-*  
43 *training* ( $d = 1.77 - 2.17$ ,  $p < 0.001$ ) but remained unchanged for the CON group ( $d = 0.20 -$   
44  $0.31$ ,  $p > 0.05$ ). BF<sub>LH</sub> volume increased more for the HE than the NHE ( $d = 1.03$ ,  $p = 0.037$ )  
45 and CON ( $d = 2.24$ ,  $p < 0.001$ ) groups. Compared to the CON group, both exercises induced  
46 significant increases in semitendinosus volume ( $d = 2.16 - 2.50$ ,  $\leq 0.002$ ), however, only the  
47 HE group displayed increased semimembranosus volume ( $d = 1.57$ ,  $p = 0.007$ ).  
48 **CONCLUSION:** NHE and HE training both stimulate significant increases in BF<sub>LH</sub> fascicle  
49 length, however, HE training may be more effective for promoting hypertrophy in the BF<sub>LH</sub>  
50 and semimembranosus than the NHE.

51

52

53

54

55

56

**What are the new findings?**

57

- Hip extension and Nordic hamstring exercise training both promote the elongation of biceps femoris long head fascicles, and stimulate improvements in eccentric knee flexor strength.

58

59

- Hip extension training promotes more hypertrophy in the biceps femoris long head and semimembranosus than the Nordic hamstring exercise, which preferentially develops the semitendinosus and the short head of biceps femoris.

## 60 INTRODUCTION

61 Hamstring ‘tears’ are endemic in sports involving high-speed running and upwards of 80% of  
62 these injuries involve the biceps femoris long head (BF<sub>LH</sub>).[1-4] Hamstring strains represent  
63 the most common injury in athletics,[5] Australian Rules football,[6 7] and soccer[8] and as  
64 many as 30% reoccur within 12 months.[9] These findings highlight the need for improved  
65 hamstring injury prevention programs while also suggesting the possibility that these programs  
66 should specifically target the BF<sub>LH</sub>.

67 There has been significant interest in exploring the patterns of muscle activity in hamstring  
68 exercises,[10-15] however there is no research examining the architectural and morphological  
69 adaptations of these muscles to different exercise interventions. The Nordic hamstring exercise  
70 (NHE) has proven effective in increasing eccentric knee flexor strength[16] and reducing  
71 hamstring injuries[17-19] in soccer, although there is disagreement in the literature as to which  
72 hamstring muscles are most active during this exercise[10 14 15 20]. We have previously  
73 reported that the NHE preferentially activates the semitendinosus (ST),[10 15] however, we  
74 have also observed high levels of BF<sub>LH</sub> activity in this exercise[15] which suggests that it may  
75 still provide a powerful stimulus for adaptation within this most commonly injured muscle.[1-  
76 4] Eccentric exercise has been proposed to increase muscle fascicle lengths via  
77 sarcomerogenesis[21 22] and Timmins and colleagues[23] have recently observed such an  
78 adaptation after eccentric knee flexor training on an isokinetic dynamometer while also noting  
79 that concentric training caused fascicle shortening despite occurring at long muscle lengths.  
80 Furthermore, we have recently reported that soccer players with shorter BF<sub>LH</sub> fascicles  
81 (<10.56cm) were at fourfold greater risk of hamstring strain injury than players with longer  
82 fascicles.[23] Given the effectiveness of the predominantly eccentric NHE in hamstring injury  
83 prevention and rehabilitation,[17-19] it is of interest to examine the impact of this and  
84 alternative exercises on BF<sub>LH</sub> fascicle lengths and morphology.

85 We have recently observed that the 45° hip extension (HE) exercise resulted in more uniform  
86 activation of the two-joint hamstrings and greater  $BF_{LH}$  activity than the NHE[15]. HE  
87 exercises are also performed at longer hamstring muscle lengths than the NHE and it has been  
88 suggested that this may make them more effective in hamstring injury prevention than the  
89 NHE.[24] However, HE and most other hamstring exercises are typically performed with both  
90 eccentric and concentric phases and it remains to be seen how the combination of contraction  
91 modes will affect fascicle length by comparison with an almost purely eccentric exercise like  
92 the NHE. Nevertheless, the greater activation of  $BF_{LH}$  during HE[10 15] may provide a greater  
93 stimulus for hypertrophy, which might have implications for rehabilitation practices given  
94 observations of persistent atrophy in this muscle following injury.[25]

95 The primary purpose of this study was to evaluate changes in  $BF_{LH}$  architecture and hamstring  
96 muscle volume and anatomical cross-sectional area (ACSA) following 10-week resistance  
97 training programs consisting exclusively of NHE or HE training. We tested the hypotheses that  
98 1) HE training would stimulate greater increases in  $BF_{LH}$  fascicle length than the NHE, on the  
99 basis of the suggestion that the ‘elongation stress’ in hamstring exercises may be an important  
100 factor in triggering this adaptation[24]; 2) HE training would promote more  $BF_{LH}$  hypertrophy  
101 than the NHE; and 3) the NHE would result in more hypertrophy of the ST muscle than the HE  
102 exercise.

103

104 **METHODS**

105 **Participants**

106 Thirty recreationally active males (age,  $22.0 \pm 3.6$  years, height,  $180.4 \pm 7$  cm, weight,  $80.8 \pm$   
107  $11.1$  kg) provided written informed consent to participate in this study. Participants  
108 were free from soft tissue and orthopaedic injuries to the trunk, hips and lower limbs and had  
109 no known history of hamstring strain, anterior cruciate ligament or other traumatic knee injury.  
110 Before enrolment in the study, all participants completed a cardiovascular screening  
111 questionnaire and a standard MRI questionnaire to ensure it was safe for them to enter the  
112 magnetic field. This study was approved by the Queensland University of Technology Human  
113 Research Ethics Committee and the University of Queensland Medical Research Ethics  
114 Committee.

115 **Study design**

116 This longitudinal training study was conducted between April and June, 2015. Approximately  
117 one week before the intervention commenced, participants underwent MR and 2D ultrasound  
118 imaging of their posterior thighs to determine hamstring muscle size and  $BF_{LH}$  architecture,  
119 respectively. After scanning, all participants were familiarised with the NHE and  $45^\circ$  HE  
120 exercise and subsequently underwent strength assessments on each exercise. After all of the  
121 pre-training assessments had been completed, participants were allocated to one of three  
122 groups: NHE, HE or control (CON). Allocation of participants to groups was performed on the  
123 basis of *baseline*  $BF_{LH}$  fascicle lengths to ensure that groups did not differ in this parameter  
124 prior to commencement of the study. Of the three participants with the longest fascicles, the  
125 first (with the longest fascicles) was allocated randomly to one of the three groups and then the  
126 second was allocated at random to one of the remaining two groups and the third allocated to  
127 the remaining group. This process was repeated for the participants with the 4<sup>th</sup> to 6<sup>th</sup> longest

128 fascicles, the 7<sup>th</sup> to 9<sup>th</sup> longest fascicles and so forth until each group had 10 participants. The  
129 NHE and HE groups completed a 10-week progressive strength training program consisting  
130 exclusively of their allocated exercise (Table 1). The CON group were advised to continue  
131 their regular physical activity levels but not to engage in any resistance training for the lower  
132 body. At the beginning of every training session, participants in both training groups reported  
133 their level of perceived soreness in the posterior thigh using a 1-10 numeric pain rating scale.  
134 All CON participants were required to report to the laboratory at least once per week. For all  
135 participants, BF<sub>LH</sub> architecture was re-assessed 5 weeks into the intervention and within 5 days  
136 of the final training session. MRI scans were acquired for all participants <7 days after the final  
137 training session. Strength testing was conducted after all imaging had been completed.

### 138 **Training intervention**

#### 139 *Nordic hamstring exercise (NHE)*

140 An illustration of the NHE can be found in Figure 1a (see also video supplement). Participants  
141 knelt on a padded board, with the ankles secured immediately superior to the lateral malleolus  
142 by individual ankle braces which were attached to uniaxial load cells. The ankle braces and  
143 load cells were secured to a pivot which allowed the force generated by the knee flexors to be  
144 measured through the long axis of the load cells. From the initial kneeling position with their  
145 ankles secured in yokes, arms on the chest and hips extended, participants lowered their bodies  
146 as slowly as possible to a prone position.[10] Participants performed only the lowering  
147 (eccentric) portion of the exercise and were instructed to use their arms and flex at the hips and  
148 knees to push back into the starting position so as to minimise concentric knee flexor activity.  
149 When participants developed sufficient strength to completely stop the movement in the final  
150 10-20° of the range of motion, they were required to hold a weight plate (range = 2.5kg to

151 20kg) to their chest (centred to the xiphoid process) to ensure the exercise was still of  
152 supramaximal intensity. Participants were provided with 3min of rest between each set.

153 *Hip extension exercise (HE)*

154 Participants were positioned in a 45° hip extension machine (BodySolid, IL, USA) with their  
155 trunk erect and hip joints extended and superior to the level of support pad (Figure 1b; see also  
156 video supplement). The ankle of the exercised limb was ‘hooked’ under an ankle pad and the  
157 unexercised limb was allowed to rest above its ankle restraint. Participants held one or more  
158 circular weight plate(s) to the chest (centred to the xiphoid process) and were instructed to flex  
159 their hip until they reached a point approximately 90° from the starting position. Once  
160 participants had reached this position they were instructed to return to the starting position by  
161 extending their hip, while keeping their trunk in a rigid neutral position throughout. Both limbs  
162 were trained in alternating fashion; after completing a set on one limb participants rested for  
163 30s before training the opposite limb, and then recovered for 3min before the next set. The load  
164 held to the chest in week 1 represented 60-70% of the estimated 1-RM and was progressively  
165 increased throughout the training period whenever the prescribed repetitions and sets could be  
166 completed with appropriate technique (Table 2).

167

168 INSERT FIGURE 1

169

170 **Hamstring training program**

171 Participants in both intervention groups completed a progressive intensity training program  
172 consisting of 20 supervised exercise sessions (2 per week) over the 10 week period (Tables 1  
173 & 2). Each session was followed by at least 48 hours of recovery and participants were

174 prohibited from engaging in any other resistance training for the lower body. The training  
 175 program was based on the approximate loads, repetitions and sets employed in previous  
 176 interventions using the NHE,[16-18] although the volume (number of repetitions) was reduced  
 177 in the final two weeks to accommodate increases in exercise intensity. All sessions were  
 178 conducted in the same laboratory, employed the same exercise equipment and were supervised  
 179 by the same investigators (MNB and SJD) to ensure consistency of procedures.

180 **Table 1. Training program variables for both the Nordic hamstring and hip extension**  
 181 **training groups**

<b>Week</b>	<b>Frequency</b>	<b>Sets</b>	<b>Repetitions</b>
<b>1</b>	2	2	6
<b>2</b>	2	3	6
<b>3</b>	2	4	8
<b>4</b>	2	4	10
<b>5-8</b>	2	5	8-10
<b>9</b>	2	6	6
<b>10</b>	2	5	5

182

183 **Table 2. Application of progressive overload for both the Nordic hamstring and hip**  
 184 **extension training groups**

<b>Week</b>	<b>Training Intensity (Load)</b>	
	<b>Nordic Hamstring exercise</b>	<b>Hip extension exercise</b>
<b>1</b>	Load was added to the chest in increments of 2.5kg when participants developed sufficient strength to stop at the end of the range of motion.	60-70% of 1-RM
<b>2</b>		70-80% of 1-RM
<b>3</b>		All exercise was completed at maximal intensity of effort. Loads were progressively increased when
<b>4</b>		
<b>5-8</b>		
<b>9</b>		

10		desired repetitions and sets were achieved.
----	--	---

185

186

187 **Strength assessments**

188 Before and <7 days after the intervention, all participants underwent an assessment of their  
 189 maximal eccentric knee-flexor strength during three repetitions of the NHE, and their 3-  
 190 repetition maximum (3-RM) strength on the 45° hip extension machine. All strength tests were  
 191 conducted by the same investigators (MNB, SJD and AJS) with tests completed at  
 192 approximately the same time of day before and after the intervention.

193 *Nordic eccentric strength test*

194 The assessment of eccentric knee flexor force using the NHE has been reported previously.[3  
 195 4 23 26] Participants completed a single warm-up set of 5 submaximal repetitions followed, 1  
 196 minute later, by a set of 3 maximal repetitions of the bilateral NHE. Eccentric strength was  
 197 determined for each leg from the highest of 3 peak forces produced during the 3 repetitions of  
 198 the NHE and was reported in absolute terms (N).

199 *Hip extension strength test*

200 All strength assessments on the 45° hip extension machine were conducted unilaterally.  
 201 Participants initially warmed up by performing 8-10 repetitions on each leg using body weight  
 202 only. Subsequently, loads held to the chest were progressively increased until investigators  
 203 determined the maximal load that could be lifted three times. At least 2min of rest was provided  
 204 between sets.

205 **BF<sub>LH</sub> architecture assessment**

206 BF<sub>LH</sub> fascicle length was determined from ultrasound images taken along the longitudinal axis  
207 of the muscle belly utilising a two-dimensional, B-mode ultrasound (frequency, 12Mhz; depth,  
208 8cm; field of view, 14 x 47mm) (GE Healthcare Vivid-i, Wauwatosa, U.S.A). Participants were  
209 positioned prone on a plinth with their hips in neutral and knees fully extended, while images  
210 were acquired from a point midway between the ischial tuberosity and the knee joint fold,  
211 parallel to the presumed orientation of BF<sub>LH</sub> fascicles. After the scanning site was determined,  
212 the distance of the site from various anatomical landmarks were recorded to ensure its  
213 reproducibility for future testing sessions. These landmarks included the ischial tuberosity,  
214 head of the fibula and the posterior knee joint fold at the mid-point between BF and ST tendon.  
215 On subsequent visits the scanning site was determined and marked on the skin and then  
216 confirmed by replicated landmark distance measures. Images were obtained from both limbs  
217 following at least five minutes of inactivity. To gather ultrasound images, the linear array  
218 ultrasound probe, with a layer of conductive gel was placed on the skin over the scanning site,  
219 aligned longitudinally and perpendicular to the posterior thigh. Care was taken to ensure  
220 minimal pressure was placed on the skin by the probe as this may influence the accuracy of the  
221 measures.[27] The orientation of the probe was manipulated slightly by the sonographer (RGT)  
222 if the superficial and intermediate aponeuroses were not parallel.

223 Ultrasound images were analysed using MicroDicom software (Version 0.7.8, Bulgaria). For  
224 each image, 6 points were digitised as described by Blazeovich and colleagues.[28] Following  
225 the digitising process, muscle thickness was defined as the distance between the superficial and  
226 intermediate aponeuroses of the BF<sub>LH</sub>. A fascicle of interest was outlined and marked on the  
227 image (Figure 2). Fascicle length was determined as the length of the outlined fascicle between  
228 aponeuroses and was reported in absolute terms (cm). As the entire fascicles were not visible  
229 in the probe's field of view, their lengths were estimated using the following equation:[28 29]

230 
$$FL = \sin(AA + 90^\circ) \times MT / \sin(180^\circ - (AA + 180^\circ - PA)).$$

231 Where  $FL$ =fascicle length,  $AA$ =aponeurosis angle,  $MT$ =muscle thickness and  $PA$ =pennation  
232 angle.

233 All images were collected and analysed by the same investigator (RGT) who was blinded to  
234 training group allocation. The assessment of  $BF_{LH}$  architecture using the aforementioned  
235 procedures by this investigator (RGT) is highly reliable (intraclass correlations >0.90).[30]

236

237 **INSERT FIGURE 2**

238 **Muscle volumes and anatomical cross-sectional area assessment** All MRI scans were  
239 performed using a 3-Tesla (Siemens TrioTim, Germany) imaging system with a spinal coil.  
240 The participant was positioned supine in the magnet bore with the knees fully extended and  
241 hips in neutral, and straps were placed around both limbs to prevent any undesired movement.  
242 Contiguous T1-weighted axial MR images (transverse relaxation time: 750ms; echo time:  
243 12ms; field of view: 400mm; slice thickness: 10mm; interslice distance: 0mm) were taken of  
244 both limbs beginning at the iliac crest and finishing distal to the tibial condyles. A localiser  
245 adjustment (20s) was applied prior to the acquisition of T1-weighted images to standardise the  
246 field of view. In addition, to minimise any inhomogeneity in MR images caused by dielectric  
247 resonances at 3T, a post-processing (B1) filter was applied to all scans.[31] The total scan  
248 duration was 3min 39sec.

249 Muscle volumes and anatomical cross-sectional areas (ACSAs) of the  $BF_{LH}$  and short head  
250 ( $BF_{SH}$ ), semitendinosus (ST) and semimembranosus (SM) muscles were determined for both  
251 limbs using manual segmentation. Muscle boundaries were identified and traced on each image  
252 in which the desired structure was present using image analysis software (Sante Dicom Viewer

253 and Editor, Cornell University) (Figure 3). Volumes were determined for each muscle by  
254 multiplying the summed CSAs (from all the slices containing the muscle of interest) by the  
255 slice thickness.[25] ACSA was determined by locating the 10mm slice with the greatest CSA  
256 and averaging this along with the two slices immediately cranial and caudal (five slices). All  
257 traces (pre- and post-training) were completed by the same investigator (MNB) who was  
258 blinded to participant identity and training group in all post-testing.

259

260

INSERT FIGURE 3

### 261 **Statistical analysis**

262 All statistical analyses were performed using SPSS version 22.0.0.1 (IBM Corporation,  
263 Chicago, IL). Repeated measures split plot ANOVAs were used to determine training-induced  
264 changes in BF<sub>LH</sub> architecture, hamstring muscle volumes and ACSA, strength, and ratings of  
265 perceived soreness, for each group. For the analysis of BF<sub>LH</sub> fascicle length, the within-subject  
266 variable was *time* (*baseline, mid-training, and post-training*) and the between-subject variable  
267 was *group* (HE, NHE, CON). Because BF<sub>LH</sub> architecture did not differ between limbs  
268 (dominant vs non-dominant) at any time point ( $p>0.05$ ), the left and right limbs were averaged  
269 to provide a single value for each participant. To determine differences in the percentage  
270 change in hamstring muscle volume and ACSA between groups, the within-subject variable  
271 was *muscle* (BF<sub>LH</sub>, BF<sub>SH</sub>, ST, and SM) and the between-subject variable was *group* (HE, NHE,  
272 CON). To explore changes in Nordic and 45° hip extension strength the within-subject variable  
273 was *time* (*baseline and post-training*) and the between-subject variable was *group* (HE, NHE,  
274 CON). Lastly, to determine if ratings of perceived soreness changed over time, or differed  
275 between training groups, within-subject variable was *time* (weeks 1-10) and the between-  
276 subject variable was *group* (HE, NHE, CON) For all analyses, when a significant main effect

277 was detected, post hoc independent t tests with Bonferroni corrections were used to determine  
278 which comparisons differed. For all analyses, the mean differences were reported with their  
279 95% confidence intervals (CIs), and where appropriate, Cohen's *d* was reported as a measure  
280 of the effect size.

### 281 **Sample size**

282 *A priori* sample size estimates were based on anticipated differences in BF<sub>LH</sub> fascicle length  
283 following the training intervention. A sample size of 10 in each group was calculated to provide  
284 sufficient statistical power (80%) to detect an effect size of 1.0 for the difference in fascicle  
285 length changes between training groups, with  $p < 0.05$ .

286

287

288 **RESULTS**

289

290 No significant differences were observed in age, height or body mass between the three groups  
291 ( $p > 0.05$ ) (Table 3). Compliance rates were excellent for both training groups (HE: 100%;  
292 NHE: 99.5%).

293

294 **Table 3. Participant characteristics**

295

<b>Group</b>	<b>Age (years)</b>	<b>Height (cm)</b>	<b>Mass (kg)</b>
<b>HE</b>	23.1±4.1	180±6.3	81.6±9.7
<b>NHE</b>	21.6±3.2	182.8±8.7	85.0±10.9
<b>CON</b>	21.3±3.7	178.5±5.4	75.9±11.8

296

297

298 **Biceps femoris long head (BF<sub>LH</sub>) fascicle length**

299 *Between-group comparisons*

300 A significant *group x time* interaction was observed for fascicle length during the training  
301 period ( $p < 0.001$ ) (Figure 4). No significant differences were observed between training groups  
302 at either *baseline* ( $d = 0.15$ ), *mid-* ( $d = 0.49$ ) or *post-training* points ( $d = 0.80$ ) (all  $p > 0.05$ ).  
303 However, the NHE group displayed significantly longer fascicles than the CON group at *mid-*  
304 (mean difference = 1.50cm, 95% CI = 0.58 to 2.41cm,  $d = 1.64$ ,  $p = 0.001$ ) and *post-training*  
305 (mean difference = 2.40cm, 95% CI = 1.28 to 3.53cm,  $d = 2.19$ ,  $p < 0.001$ ). Similarly, the HE  
306 group exhibited significantly longer fascicles than the CON group at *mid-* (mean difference =  
307 1.14cm, 95% CI = 0.22 to 2.05cm,  $d = 1.52$ ,  $p = 0.011$ ) and *post-training* (mean difference =  
308 1.63cm, 95% CI = 0.51 to 2.76cm,  $d = 1.84$ ,  $p = 0.003$ ).

309 *Within-group comparisons*

310 Post hoc analyses revealed that BF<sub>LH</sub> fascicle length increased significantly from *baseline* in  
311 the NHE group at *mid-* (mean difference = 1.23cm, 95% CI = 0.84 to 1.63cm,  $d = 1.39$ ,  $p <$   
312  $0.001$ ) and *post-training* (mean difference = 2.22cm, 95% CI = 1.74 to 2.69cm,  $d = 2.17$ ,  $p <$   
313  $0.001$ ). The HE group also displayed significantly lengthened fascicles at *mid-* (mean  
314 difference = 0.75cm, 95% CI = 0.35 to 1.15cm,  $d = 1.12$ ,  $p < 0.001$ ) and *post-training* (mean  
315 difference = 1.33cm, 95% CI = -0.86 to 1.80cm,  $d = 1.77$ ,  $p < 0.001$ ). However, the CON group  
316 remained unchanged relative to *baseline* values at all time points ( $p > 0.05$ ,  $d = 0.20 - 0.31$ ).

317 INSERT FIGURE 4

318

319 **Hamstring muscle volumes**

320 *Between-group comparisons*

321 A significant main effect was detected for the *muscle x group* interaction for hamstring muscle  
322 volume changes ( $p < 0.001$ ) (Figure 5). BF<sub>LH</sub> volume increased significantly more in the HE  
323 than the NHE (mean difference = 6.72%, 95% CI = 0.32 to 13.11%,  $d = 1.03$ ,  $p = 0.037$ ) and  
324 CON groups (mean difference = 12.10%, 95% CI = 5.71 to 18.50%,  $d = 2.24$ ,  $p < 0.001$ ), and  
325 a smaller nonsignificant difference was observed between the NHE and CON groups (mean  
326 difference = 5.39%, 95% CI = -1.01 to 11.78%,  $d = 1.13$ ,  $p = 0.122$ ) (Figure 5). BF<sub>SH</sub> volume  
327 increased more in the HE (mean difference = 8.51%, 95% CI = 0.17 to 16.85%,  $d = 1.49$ ,  $p =$   
328  $0.044$ ) and NHE groups (mean difference = 15.29%, 95% CI = 6.95 to 23.63%,  $d = 2.09$ ,  $p <$   
329  $0.001$ ) than in the CON group. Both the NHE (mean difference = 21.21%, 95% CI = 11.55 to  
330 30.88%,  $d = 2.50$ ,  $p < 0.001$ ) and HE (mean difference = 14.32%, 95% CI = 4.65 to 23.98%,  
331  $d = 2.16$ ,  $p = 0.002$ ) training groups exhibited a greater increase in ST volume than the CON  
332 group. However, no significant difference in ST volume change was noted between NHE and

333 HE groups (mean difference = 6.90%, 95% CI = -2.77 to 16.56%,  $d = 0.69$ ,  $p = 0.239$ ). The  
334 percentage change in volume for the SM was significantly greater for the HE group than for  
335 CON (mean difference = 8.95%, 95% CI = 2.21 to 15.69%,  $d = 1.57$ ,  $p = 0.007$ ), while no  
336 difference was observed between the NHE and CON group changes (mean difference = 3.38%,  
337 95% CI = -3.36 to 10.12%,  $d = 0.68$ ,  $p = 0.636$ ) for this muscle.

### 338 *Within-group comparisons*

339 HE training stimulated a greater increase in volume for the ST than the BF<sub>SH</sub> (mean difference  
340 = 5.61%, 95% CI = 1.12% to 10.10%,  $d = 0.71$ ,  $p = 0.009$ ). No other significant between-  
341 muscle differences were noted for volume changes after HE training ( $p=0.054 - 0.999$  for all  
342 pairwise comparisons) or in the CON group ( $p > 1.000$ ). After NHE training, ST volume  
343 increased more than BF<sub>LH</sub> (mean difference = 15.28%, 95% CI = 10.69 to 19.87%,  $d = 3.54$ ,  
344  $p < 0.001$ ) and SM (mean difference = 16.06%, 95% CI = 10.96 to 21.16%,  $d = 3.53$ ,  $p < 0.001$ ).  
345 Similarly, in the NHE group the percentage change in volume was greater for the BF<sub>SH</sub> than  
346 the BF<sub>LH</sub> (mean difference = 9.56%, 95% CI = 4.30 to 14.80%,  $d = 1.18$ ,  $p < 0.001$ ) and SM  
347 (mean difference = 10.33%, 95% CI = 5.33 to 15.34%,  $d = 1.26$ ,  $p < 0.001$ ).

348

349 INSERT FIGURE 5

350

### 351 **Hamstring muscle anatomical cross-sectional area (ACSA)**

#### 352 *Between-group comparisons*

353 A significant main effect was detected for the *muscle x group* interaction ( $p < 0.001$ ) (Figure  
354 6). The percentage change in BF<sub>LH</sub> ACSA was greater in the HE training group than in the  
355 NHE (mean difference = 5.24%, 95% CI = 0.061 to 10.41,  $d = 0.98$ ,  $p = 0.047$ ) and CON  
356 groups (mean difference = 8.90%, 95% CI = 3.73 to 14.07%,  $d = 1.94$ ,  $p < 0.001$ ), while no

357 difference was observed between the NHE and CON groups (mean difference = 3.67%, 95%  
358 CI = -1.51 to 8.84%,  $d = 1.07$ ,  $p = 0.245$ ) (Figure 6).  $BF_{SH}$  ACSA increased significantly more  
359 in the NHE than the CON group (mean difference = 13.26%, 95% CI = 4.98 to 21.54%,  $d =$   
360  $1.97$ ,  $p = 0.001$ ), while no difference was observed between changes exhibited by the HE and  
361 CON groups for this muscle (mean difference = 5.69%, 95% CI = -2.59 to 0.70%,  $d = 0.90$ ,  $p$   
362 = 0.273). The percentage change in ST ACSA was significantly greater in the NHE (mean  
363 difference = 17.60%, 95% CI = 7.60 to 27.61%,  $d = 2.17$ ,  $p < 0.001$ ) and HE (mean difference  
364 = 15.16%, 95% CI = 5.15 to 25.17%,  $d = 1.95$ ,  $p = 0.002$ ) groups than the CON group, however  
365 no significant difference was noted between changes in the NHE and HE groups (mean  
366 difference = 2.4%, 95% CI = -7.57 to 12.45%,  $d = 0.24$ ,  $p = 1.000$ ). The percentage increase  
367 in SM ACSA was greater in the HE than the CON group (mean difference = 7.19%, 95% CI =  
368 1.21 to 13.18%,  $d = 1.34$ ,  $p = 0.015$ ), but was not significantly greater in NHE than CON (mean  
369 difference = 2.02%, 95% CI = -3.97 to 8.01%,  $d = 0.49$ ,  $p = 1.000$ ). No significant difference  
370 in SM ACSA change was noted between the HE and NHE groups (main difference = 5.17%,  
371 95% CI = -8.2 to 11.16%,  $d = 0.85$ ,  $p = 0.109$ ).

#### 372 *Within-group comparisons*

373 After HE training, the change in ACSA observed for the ST was significantly greater than the  
374  $BF_{LH}$  (mean difference = 6.46, 95% CI = 0.84 to 12.10%,  $d = 0.78$ ,  $p = 0.017$ ),  $BF_{SH}$  (mean  
375 difference = 9.98%, 95% CI = 4.25 to 15.71%,  $d = 1.09$ ,  $p < 0.001$ ) and SM (mean difference  
376 = 6.73%, 95% CI = 1.54 to 11.92%,  $d = 0.78$ ,  $p = 0.006$ ). No other significant pairwise  
377 between-muscle differences in ACSA change were noted after HE training (all  $p > 0.05$ ). After  
378 NHE training, the change in ACSA was greater for  $BF_{SH}$  than  $BF_{LH}$  (mean difference = 9.30%,  
379 95% CI = 3.47 to 15.12%,  $d = 1.34$ ,  $p = 0.001$ ) and SM (mean difference = 9.50%, 95% CI =  
380 4.92 to 14.08,  $d = 1.33$ ,  $p < 0.001$ ), while ST ACSA increased more than  $BF_{LH}$  (mean difference

381 = 14.14%, 95% CI = 8.52 to 19.76%,  $d = 1.76$ ,  $p < 0.001$ ) and SM (mean difference = 14.35%,  
382 95% CI = 9.15 to 19.54%,  $d = 1.75$ ,  $p < 0.001$ ).

383

384

385

INSERT FIGURE 6

386

387

388

### 389 **Strength**

#### 390 *Nordic eccentric strength test*

391 A significant *group x time* interaction effect was observed for the Nordic eccentric strength test  
392 ( $p < 0.001$ ) (Figure 7). Post hoc t tests demonstrated that the NHE (mean difference = 97.38N,  
393 95% CI = 65.51 to 129.26N,  $d = 2.36$ ,  $p < 0.001$ ) and HE (mean difference = 110.47N, 95%  
394 CI = 76.87 to 144.07N,  $d = 1.26$ ,  $p < 0.001$ ) groups were significantly stronger at *post-training*  
395 compared to *baseline* while the CON group did not change (mean difference = 8.91N, 95% CI  
396 = -42.51 to 24.69N,  $d = 0.14$ ,  $p = 0.590$ ). No groups differed at *baseline* ( $p > 0.461$ ), however,  
397 at *post-training* the NHE (mean difference = 123.436N, 95% CI = 39.93 to 206.93N,  $d = 2.07$ ,  
398  $p = 0.003$ ) and HE (mean difference = 94.27N, 95% CI = 8.60 to 179.94N,  $d = 1.14$ ,  $p = 0.028$ )  
399 groups were both significantly stronger than the CON group. No significant difference was  
400 observed between training groups at *post-training* (mean difference = 29.16N, 95% CI = -54.34  
401 to 112.66N,  $d = 0.41$ ,  $p = 0.999$ ).

402

403

INSERT FIGURE 7

404

405 *Hip extension strength test*

406 A significant *group x time* interaction effect was also observed for 3-RM strength as assessed  
407 during the 45° HE strength test ( $p < 0.001$ ) (Figure 8). Post hoc analyses demonstrated that the  
408 HE (mean difference = 41.00kg, 95% CI = 35.97 to 46.03kg,  $d = 4.59$ ,  $p < 0.001$ ) and NHE  
409 groups (mean difference = 26.00kg, 95% CI = 20.97 to 31.03kg,  $d = 2.36$ ,  $p < 0.001$ ) improved  
410 significantly from *baseline* whereas the CON group did not change (mean difference = 3.50kg,  
411 95% CI = -1.53 to 8.53kg,  $d = 0.33$ ,  $p = 0.165$ ). No groups differed significantly at *baseline* ( $p$   
412  $> 0.091$ ) however at *post-training*, both the HE (mean difference = 43.50kg, 95% CI = 30.93  
413 to 56.07kg,  $d = 4.21$ ,  $p < 0.001$ ) and NHE groups (mean difference = 32.0kg, 95% CI = 19.43  
414 to 44.57kg,  $d = 2.66$ ,  $p < 0.001$ ) were significantly stronger than CON. *Post-training*, no  
415 significant difference was observed between training groups (mean difference = 11.50kg, 95%  
416 CI = -1.07 to 24.07kg,  $d = 1.09$ ,  $p = 0.082$ ).

417

418

419

INSERT FIGURE 8

420

421 **Perceived soreness**

422 No significant *group x time* interaction effect ( $p = 0.397$ ) was detected for ratings of perceived  
423 soreness throughout the intervention (Figure 9). The average soreness measures reported across  
424 the 10-week training period were  $2.2 \pm 0.4$  (mean  $\pm$  SE) for the NHE group and  $2.3 \pm 0.5$  for  
425 the HE group.

426

427

INSERT FIGURE 9

428

429

430

431

432 **DISCUSSION**

433 This study is the first to explore the architectural and morphological adaptations of the  
434 hamstrings in response to different strength training exercises. These data suggest that both the  
435 HE and NHE stimulate significant increases in  $BF_{LH}$  fascicle length and, contrary to our  
436 hypothesis, that the longer muscle lengths encountered in the HE exercise do not result in  
437 greater lengthening of fascicles than are observed after NHE training. As hypothesised, HE  
438 training appears to elicit more hypertrophy in the  $BF_{LH}$  than does the NHE; while contrary to  
439 our hypothesis, the NHE was not significantly more effective at increasing ST volume or cross  
440 sectional area than the HE. Both exercises resulted in significant strength increases which were  
441 similarly evident in the NHE and HE strength tests.

442 Fascicle lengthening is one possible mechanism by which the NHE[17-19] and other eccentric  
443 or long length hamstring exercises[22] protect muscles from injury. We have recently shown,  
444 prospectively, that professional soccer players with fascicles  $<10.56\text{cm}$  were  $\sim 4$  times more  
445 likely to suffer a hamstring strain than athletes with longer fascicles and that the probability of  
446 injury was reduced by  $\sim 74\%$  for every  $0.5\text{cm}$  increase in fascicle length.[23] In the current  
447 study, participants increased their fascicle lengths from  $\sim 10.6\text{cm}$  prior to training, to  $12.8$  and  
448  $12.0\text{cm}$  in the NHE and HE groups, respectively, which would likely result in large reductions  
449 in hamstring injury risk.

450 Despite its success in reducing hamstring strain injuries, the adoption of the NHE in elite  
451 European soccer has been reported to be poor with only  $\sim 11\%$  of Norwegian premier league  
452 and UEFA teams deemed to have adequately implemented the NHE programs that have proven  
453 effective in randomised controlled trials[17-19]. Some conditioning coaches and  
454 researchers[24] believe that the exercise does not challenge the hamstrings at sufficient lengths  
455 to optimise injury prevention benefits. However, this study shows, for the first time, that the  
456 limited excursion of the hamstrings during the NHE does not prevent the exercise from

457 increasing  $BF_{LH}$  fascicle length. Indeed, the exercise resulted in greater fascicle lengthening  
458 than the HE, although the current study lacked the statistical power to distinguish between the  
459 two. Together with observations that long length concentric hamstring training can shorten  
460 muscle fascicles,[33] the current findings are consistent with the possibility that the  
461 combination of concentric and eccentric contractions somewhat dampens the elongation of  
462  $BF_{LH}$  fascicles. The advantage of the NHE may be its almost purely eccentric or eccentrically-  
463 biased nature. Further work is needed to clarify whether eccentrically-biased or purely  
464 eccentric HE exercise may yield greater improvements in  $BF_{LH}$  fascicle length than the  
465 combined concentric and eccentric contraction modes used in this investigation.

466 Observations of increased fascicle length following eccentric hamstring exercise are largely  
467 consistent with existing literature. For example, Potier and colleagues[32] reported a 34%  
468 increase in  $BF_{LH}$  fascicle length following eight weeks of eccentric leg curl exercise, while  
469 Timmins and colleagues[33] reported a 16% increase in  $BF_{LH}$  fascicle length after six weeks  
470 of eccentric training on an isokinetic dynamometer.[33] These adaptations most likely result  
471 from the addition of in-series sarcomeres, as has been shown to occur within the rat vastus  
472 intermedius muscle after five days of downhill running.[34] It has been proposed that this  
473 increase in serial sarcomeres accounts for both a rightward shift in a muscle's force-length  
474 relationship,[35] while also reducing its susceptibility to damage.[21 22] However, it is also  
475 at least theoretically possible that fascicle lengthening occurs as a result of increased tendon or  
476 aponeurotic stiffness and further research is needed to clarify the precise mechanism(s)  
477 responsible for these architectural changes.

478 To the authors' knowledge, this is the first study to explore the morphological adaptations of  
479 the hamstrings to different strengthening exercises. These data suggest that the NHE and HE  
480 exercises induce heterogeneous patterns of hamstring muscle hypertrophy, with the former  
481 preferentially stimulating ST and  $BF_{SH}$  growth and the latter resulting in significantly more

482 hypertrophy of the  $BF_{LH}$  and more homogenous growth of all two-joint hamstring muscles. We  
483 have previously noted transient T2 relaxation time changes after 50 repetitions of each of these  
484 exercises that almost exactly fit this pattern,[15] so it appears that the acute changes observed  
485 via functional MRI match quite well with the hypertrophic effects observed after 10 weeks of  
486 training. However, neither muscle volume nor ACSA have been identified as risk factors for  
487 hamstring strain injury, so the exact significance of these findings is unknown. Indeed, we have  
488 previously reported that  $BF_{LH}$  muscle thickness measured via ultrasound is not a risk factor for  
489 hamstring injury in elite soccer.[23] Nevertheless,  $BF_{LH}$  muscle atrophy has been noted as long  
490 as 5-23 months after injury in recreational athletes,[25] so unilateral HE exercises may prove  
491 more beneficial than the NHE at redressing this deficit in rehabilitation. Interestingly, reduced  
492 muscle volumes of the ST have been observed 12-72 months after anterior cruciate ligament  
493 injury[36] and the results of the current investigation suggest that the NHE may be valuable in  
494 rehabilitation of this injury.

495 Hamstring strengthening is an important component of injury prevention strategies.[24 37 38]  
496 Indeed, several large scale interventions employing the NHE have shown ~65% reductions in  
497 hamstring strain injury rates in soccer [17-19] and recent prospective findings in elite  
498 Australian football[3] and soccer[23] suggest that eccentric strength improvements like those  
499 reported here and previously[16] are at least partly responsible for these protective benefits.  
500 For example, elite athletes in these sports who generated less than 279N (Australian football)  
501 and 337N (soccer) of knee flexor force at the ankles during the NHE strength test were ~4 times  
502 more likely to sustain hamstring injuries than stronger counterparts.[3 23] In this study, our  
503 recreational level athletes were able to generate, on average, 460N and 431N after 10 weeks of  
504 NHE and HE training, respectively, making them substantially stronger than these elite  
505 Australian football[3] and soccer players.[23] Significant improvements in 3-RM HE strength  
506 were also observed for both training groups, which suggests that hamstring strengthening, at

507 least in recreationally trained athletes, is not highly specific to the chosen exercise. While the  
508 benefits of high levels of HE strength remain unclear from the perspective of injury prevention,  
509 the observed effects of HE training on  $BF_{LH}$  fascicle lengths and eccentric knee flexor strength  
510 suggest the potential for this exercise to reduce injury risk. Future intervention studies  
511 analogous to those employing the NHE previously,[17-19 39] are needed to clarify whether  
512 HE training is effective in reducing hamstring strain injuries, however, access to exercise  
513 equipment (ie., a 45° HE machine) may be a limiting factor in designing such studies. It is also  
514 noteworthy that strength improvements can be achieved with very modest levels of hamstring  
515 muscle soreness when training is appropriately structured and progressively overloaded. These  
516 observations are in agreement with Mjolsnes and colleagues[16] who have previously reported  
517 very limited muscle soreness with a gradual increase in NHE volume.

518 The authors acknowledge that there are some limitations associated with the current study.  
519 Firstly, muscle architecture was only assessed in the  $BF_{LH}$  and it may not be appropriate to  
520 generalise these findings to other knee flexors, given that each hamstring muscle displays  
521 unique architectural characteristics.[40] Further, the assessment of fascicle length using two-  
522 dimensional ultrasound requires some degree of estimation, because the entire length of the  
523  $BF_{LH}$  fascicles are not visible in ultrasound images. While the estimation equation used in this  
524 study has been validated against cadaveric samples,[29] there is still the potential for error, and  
525 future studies employing extended field of view ultrasound methods may be needed to  
526 completely eliminate this. Lastly, all of the athletes in this study were recreational level males  
527 of a similar age, and it remains to be seen if these results are applicable to other populations.  
528 However, our participants were, on average, as strong as elite Australian football players[3]  
529 and stronger than professional soccer players[23] at the start of the study. Furthermore, our  
530 cohort displayed average fascicle lengths before training that were within one standard

531 deviation of the values reported in elite soccer players previously,[23] so it is unlikely that they  
532 were unrepresentative of higher-level athletes, in these parameters at least.

533 This is the first study to demonstrate that training with different exercises elicits unique  
534 architectural and morphological adaptations within the hamstring muscle group. We have  
535 provided evidence to suggest that both HE and NHE training are effective in lengthening BF<sub>LH</sub>  
536 fascicles and that the greater excursion involved in the HE does not result in greater increases  
537 in fascicle length. However, HE training appears to be more effective for promoting  
538 hypertrophy in the commonly injured BF<sub>LH</sub> than the NHE, which preferentially develops the  
539 ST and BF<sub>SH</sub> muscles. HE and NHE had very similar effects on ST volume and cross-sectional  
540 area. These data may help to explain the mechanism(s) by which the NHE confers injury  
541 preventive benefits and also provide compelling evidence to warrant the further exploration of  
542 HE-oriented exercises in hamstring strain injury prevention protocols. Future prospective  
543 studies are needed to ascertain whether HE training interventions are effective in reducing the  
544 incidence of hamstring strain injury in sport and whether or not the combination of HE and  
545 NHE training is more effective than the NHE alone.

546

547

**How might it impact upon clinical practice in the future?**

- Hip extension and Nordic hamstring exercise training are both effective in lengthening biceps femoris long head fascicles, and in promoting improvements in eccentric knee flexor strength, which may significantly reduce the risk of hamstring strain injury
- Hip extension exercise may be more useful than the Nordic hamstring exercise for stimulating hypertrophy in the commonly injured biceps femoris long head

548 **ACKNOWLEDGEMENTS**

549 The authors thank the Queensland Academy of Sport's Centre of Excellence for Applied Sport  
550 Science Research for funding this investigation. The authors also acknowledge the facilities,  
551 and the scientific and technical assistance of the National Imaging Facility at the Centre for  
552 Advanced Imaging, University of Queensland. Lastly, we thank Troy O'Donohue, Casey Sims  
553 and all other research assistants who generously volunteered their time for this project.

554 **CONTRIBUTORS**

555 MB was the principle investigator and was involved with study design, recruitment, analysis and  
556 manuscript write up. SD, RT were involved in data collection. MW, DO, GK and TS were involved  
557 with the study design, analysis and manuscript preparation. AA was involved in MRI data acquisition.  
558 All authors had full access to all of the data (including statistical reports and tables) in the study and  
559 can take responsibility for the integrity of the data and the accuracy of the data analysis.

560 **TRANSPARENCY DECLARATION**

561 The lead author\* (MB) affirms that this manuscript is an honest, accurate, and transparent account of  
562 the study being reported; that no important aspects of the study have been omitted; and that any  
563 discrepancies from the study as planned (and, if relevant, registered) have been explained. \* = The  
564 manuscript's guarantor.

565 **COPYRIGHT DECLARATION**

566 *The Corresponding Author has the right to grant on behalf of all authors and does grant on behalf of*  
567 *all authors, [a worldwide licence](#) to the Publishers and its licensees in perpetuity, in all forms, formats*  
568 *and media (whether known now or created in the future), to i) publish, reproduce, distribute, display*  
569 *and store the Contribution, ii) translate the Contribution into other languages, create adaptations,*  
570 *reprints, include within collections and create summaries, extracts and/or, abstracts of the*  
571 *Contribution, iii) create any other derivative work(s) based on the Contribution, iv) to exploit all*

572 *subsidiary rights in the Contribution, v) the inclusion of electronic links from the Contribution to third*  
573 *party material where-ever it may be located; and, vi) licence any third party to do any or all of the*  
574 *above.*

#### 575 **DATA SHARING**

576 Consent was not obtained for data sharing but the presented data are anonymised and risk of  
577 identification is low.

#### 578 **FUNDING**

579 This study was funded by the Queensland Academy of Sport's Centre of Excellence for Applied  
580 Sports Science Research.

#### 581 **COMPETING INTERESTS**

582 None declared. All authors have completed the Unified Competing Interest form  
583 at [www.icmje.org/coi\\_disclosure.pdf](http://www.icmje.org/coi_disclosure.pdf) (available on request from the corresponding author) and declare  
584 that (1) the Queensland Academy of Sport's Centre of Excellence for Applied Sports Science  
585 Research funded this study; (2) MB, SD, RT, MW, DO, GK, AA and TS have no relationships with  
586 companies that might have an interest in the submitted work in the previous 3 years; (3) their spouses,  
587 partners, or children have no financial relationships that may be relevant to the submitted work; and  
588 (4) MB, SD, RT, MW, DO, GK, AA and TS have no non-financial interests that may be relevant to  
589 the submitted work.

#### 590 **ETHICAL CLEARANCE**

591 All participants provided written, informed consent for this study, which was approved by the  
592 Queensland University of Technology Human Research Ethics Committee and the University of  
593 Queensland Medical Research Ethics Committee.

#### 594 **Figure legends**

595

596 **Figure 1.** (a) The Nordic hamstring exercise (NHE) and (b) the 45<sup>0</sup> hip extension (HE)  
597 exercise, progressive from left to right.

598 **Figure 2.** A two-dimensional ultrasound image of the biceps femoris long head (BF<sub>LH</sub>), taken  
599 along the longitudinal axis of the posterior thigh. From these images, it is possible to  
600 determine the superficial and intermediate aponeuroses, muscle thickness, and angle of the  
601 fascicle in relation to the aponeurosis. Estimates of fascicle length can then be made via  
602 trigonometry using muscle thickness and pennation angle.

603 **Figure 3.** T1-weighted image (transverse relaxation time = 750ms; echo time = 12ms, slice  
604 thickness = 10mm), depicting the regions of interest for each hamstring muscle. The *right* side  
605 of the image corresponds to the participant's *left* side as per radiology convention. BF<sub>LH</sub>, biceps  
606 femoris long head; BF<sub>SH</sub>, biceps femoris short head; ST, semitendinosus; SM,  
607 semimembranosus.

608 **Figure 4.** Biceps femoris long head (BF<sub>LH</sub>) fascicle lengths before (*baseline*), during (*mid-*  
609 *training*) and after (*post-training*) the intervention period for the hip extension (HE), Nordic  
610 hamstring exercise (NHE) and control (CON) groups. Fascicle length is expressed in absolute  
611 terms (cm) with error bars depicting standard error (SE). \* indicates p<0.05 compared to  
612 *baseline* (week 0). \*\* signifies p<0.001 compared to *baseline*. # indicates p<0.05 compared to  
613 the control group.

614 **Figure 5.** Percentage change in volume (cm<sup>3</sup>) for each hamstring muscle after the intervention.  
615 Values are expressed as a mean percentage change compared to the values at *baseline* with  
616 error bars representing standard error (SE). For all pairwise comparisons between groups, \*  
617 indicates p<0.05 and \*\* signifies that p<0.001. BF<sub>LH</sub>, biceps femoris long head; BF<sub>SH</sub>, biceps  
618 femoris short head; ST, semitendinosus; SM, semimembranosus.

619 **Figure 6.** Percentage change in anatomical cross sectional area (ACSA) (cm<sup>2</sup>) for each  
620 hamstring muscle after the intervention. Values are expressed as a mean percentage change  
621 compared to the values at *baseline* with error bars representing standard error (SE). For all  
622 pairwise comparisons between groups, \* indicates p<0.05 and \*\* signifies that p<0.001. BF<sub>LH</sub>,  
623 biceps femoris long head; BF<sub>SH</sub>, biceps femoris short head; ST, semitendinosus; SM,  
624 semimembranosus.

625 **Figure 7.** Eccentric knee flexor force measured during the Nordic strength test before  
626 (*baseline*) and after (*post-training*) the intervention period for the hip extension (HE), Nordic  
627 hamstring exercise (NHE) and control (CON) groups. Force is reported in absolute terms (N)  
628 with error bars depicting standard error (SE). \* indicates p<0.001 compared to *baseline* (week  
629 0). # signifies p<0.05 compared to the control group.

630 **Figure 8.** Hip extension three-repetition maximum (3RM) before (*baseline*) and after (*post-*  
631 *training*) the intervention period for the hip extension (HE), Nordic hamstring exercise (NHE)  
632 and control (CON) groups. Force is reported in absolute terms (kg) with error bars depicting  
633 standard error (SE). \*\* indicates p<0.001 compared to *baseline* (week 0). # signifies p<0.001  
634 compared to the control group.

635 **Figure 9.** Mean ( $\pm$  standard error) weekly soreness measured using a numeric pain rating scale  
636 (1-10) at the beginning of each training session.

637 **References**

- 638 1. Verrall GM, Slavotinek JP, Barnes PG, et al. Diagnostic and prognostic value of clinical  
639 findings in 83 athletes with posterior thigh injury: comparison of clinical findings with  
640 magnetic resonance imaging documentation of hamstring muscle strain. *Am J Sports*  
641 *Med* 2003;31(6):969-73  
642
- 643 2 Koulouris G, Connell DA, Brukner P, et al. Magnetic Resonance Imaging Parameters for  
644 Assessing Risk of Recurrent Hamstring Injuries in Elite Athletes. *Am J Sports Med*  
645 2007;35(9):1500-06.  
646
- 647 3. Opar DA, Williams MD, Timmins RG, et al. Eccentric Hamstring Strength and Hamstring  
648 Injury Risk in Australian Footballers. *Med Sci Sports Exerc* 2014;47(4):857-65.  
649
- 650 4. Bourne M, Opar DA, Williams M, Shield, AJ. Eccentric Knee-flexor Strength and Hamstring  
651 Injury Risk in Rugby Union: A Prospective Study. *Am J Sports Med* 2015;43(11):2663-  
652 70  
653
- 654 5. Opar DA, Drezner J, Shield A, et al. Acute hamstring strain injury in track-and-field athletes:  
655 A 3-year observational study at the Penn Relay Carnival. *Scand J Med Sci Sports* 2013;  
656 24 (4): 254–259.  
657
- 658 6. Orchard JW, Seward H, Orchard JJ. Results of 2 decades of injury surveillance and public  
659 release of data in the Australian Football League. *Am J Sports Med* 2013;41(4):734-41.  
660
- 661 7. Orchard J, Seward H. Epidemiology of injuries in the Australian Football League; seasons  
662 1997-2000. *Br J Sports Med* 2002;36(1):39-44.  
663
- 664 8. Ekstrand J, Hagglund M, Walden M. Injury incidence and injury patterns in professional  
665 football: the UEFA injury study. *Br J Sports Med* 2011;45(7):553-8.  
666
- 667 9. Orchard J, Best TM. The management of muscle strain injuries: an early return versus the  
668 risk of recurrence. *Clin J Sport Med* 2002;12(1):3-5.  
669
- 670 10. Bourne M, Opar,DA, Williams,MD, Al Najjar, A, Shield, AJ Muscle activation patterns  
671 in the Nordic hamstring exercise: Impact of prior strain injury. *Scand J Med Sci Sports*  
672 2015 doi: 10.1111/sms.12494.  
673
- 674 11. Ono T, Higashihara A, Fukubayashi T. Hamstring functions during hip-extension exercise  
675 assessed with electromyography and magnetic resonance imaging. *Res Sports Med*  
676 2011;19(1):42-52.  
677
- 678 12. Ono T, Okuwaki T, Fukubayashi T. Differences in activation patterns of knee flexor  
679 muscles during concentric and eccentric exercises. *Res Sports Med* 2010;18(3):188-98.  
680
- 681 13. Zebis MK, Skotte J, Andersen CH, et al. Kettlebell swing targets semitendinosus and supine  
682 leg curl targets biceps femoris: an EMG study with rehabilitation implications. *Br J*  
683 *Sports Med* 2013;47(18):1192-8.  
684

- 685 14. Mendiguchia J, Arcos AL, Garrues MA, et al. The use of MRI to evaluate posterior thigh  
686 muscle activity and damage during Nordic hamstring exercise. *J Strength Cond Res*  
687 2013;27 (12):3426–3435.  
688
- 689 15. Bourne MN WM, Opar DA, Al Najjar A, Shield AJ. Impact of exercise selection on  
690 hamstring muscle activation. *Br J Sports Med Published Online First: 13 May 2016*  
691 *doi:10.1136/bjsports-2015-095739*  
692
- 693 16. Mjolsnes R, Arnason A, Osthagen T, et al. A 10-week randomized trial comparing eccentric  
694 vs. concentric hamstring strength training in well-trained soccer players. *Scand J Med*  
695 *Sci Sports* 2004;14(5):311-7  
696
- 697 17. Petersen J, Thorborg K, Nielsen MB, et al. Preventive Effect of Eccentric Training on Acute  
698 Hamstring Injuries in Men’s Soccer: A Cluster-Randomized Controlled Trial. *Am J*  
699 *Sports Med* 2011;39(11):2296-303.  
700
- 701 18. van der Horst N, Smits DW, Petersen J, et al. The preventive effect of the nordic hamstring  
702 exercise on hamstring injuries in amateur soccer players: a randomized controlled trial.  
703 *Am J Sports Med* 2015;43(6):1316-23.  
704
- 705 19. Arnason A, Andersen TE, Holme I, et al. Prevention of hamstring strains in elite soccer: an  
706 intervention study. *Scand J Med Sci Sports* 2008;18(1):40-8.  
707
- 708 20. Ditroilo M, De Vito G, Delahunt E. Kinematic and electromyographic analysis of the  
709 Nordic Hamstring Exercise. *J Electromyogr Kinesiol* 2013;23(5):1111-8.  
710
- 711 21. Lynn R, Talbot J, Morgan D. Differences in rat skeletal muscles after incline and decline  
712 running. *J Appl Physiol* (1985).1998;85(1):98-104.  
713
- 714 22. Brockett C, Morgan D, Proske U. Human hamstring muscles adapt to eccentric exercise by  
715 changing optimum length. *Med Sci Sports Exerc* 2001;33(5):783-90.  
716
- 717 23. Timmins R, Bourne M, Shield A, et al. Short biceps femoris fascicles and eccentric knee flexor  
718 weakness increase the risk of hamstring injury in elite football (soccer): a prospective cohort  
719 study. *Br J Sports Med* In press. doi: 10.1136/bjsports-2015-095362.  
720
- 721 24. Guex K, Millet GP. Conceptual framework for strengthening exercises to prevent hamstring  
722 strains. *Sports Med* 2013;43(12):1207-15.  
723
- 724 25. Silder A, Heiderscheid B, Thelen D, et al. MR observations of long-term musculotendon  
725 remodeling following a hamstring strain injury. *Skeletal Radiol* 2008;37:1101-09.  
726
- 727 26. Opar DA, Piatkowski T, Williams MD, et al. A novel device using the Nordic hamstring  
728 exercise to assess eccentric knee flexor strength: a reliability and retrospective injury  
729 study. *J Orthop Sports Phys Ther* 2013;43(9):636-40.  
730
- 731 27. Klimstra M, Dowling J, Durkin JL, et al. The effect of ultrasound probe orientation on  
732 muscle architecture measurement. *J Electromyogr Kinesiol* 2007;17(4):504-14.  
733

- 734 28. Blazevich AJ, Gill ND, Zhou S. Intra- and intermuscular variation in human quadriceps  
735 femoris architecture assessed in vivo. *J Anat* 2006;209(3):289-310.  
736
- 737 29. Kellis E, Galanis N, Natsis K, et al. Validity of architectural properties of the hamstring  
738 muscles: correlation of ultrasound findings with cadaveric dissection. *J Biomech*  
739 2009;42(15):2549-54.  
740
- 741 30. Timmins RG, Shield AJ, Williams MD, et al. Biceps femoris long-head architecture: a  
742 reliability and retrospective injury study. *Med Sci Sports Ex* 2015;47(5):905-13.  
743
- 744 31. de Sousa PL, Vignaud A, Fleury S, et al. Fast monitoring of T(1) , T(2) , and relative proton  
745 density (M(0) ) changes in skeletal muscles using an IR-TrueFISP sequence. *J Magn*  
746 *Reson Imaging* 2011;33(4):921-30.  
747
- 748 32. Potier TG, Alexander CM, Seynnes OR. Effects of eccentric strength training on biceps  
749 femoris muscle architecture and knee joint range of movement. *Eur J Appl Physiol*  
750 2009;105(6):939-44.  
751
- 752 33. Timmins RG, Ruddy JD, Presland J, et al. Architectural changes of the biceps femoris after  
753 concentric or eccentric training. *Med Sci Sports Ex* 2015 [Epub ahead of print]. doi:  
754 10.1136/bjsports-2015-094881.  
755
- 756 34. Lynn R, Morgan D. Decline running produces more sarcomeres in rat vastus intermedius  
757 muscle fibers than does incline running. *J App Physiol* 1994;77(3):1439-44.  
758
- 759 35. Reeves ND, Narici MV, Maganaris CN. In vivo human muscle structure and function:  
760 adaptations to resistance training in old age. *Exp Physiol* 2004;89(6):675-89.  
761
- 762 36. Nomura Y, Kuramochi R, Fukubayashi T. Evaluation of hamstring muscle strength and  
763 morphology after anterior cruciate ligament reconstruction. *Scand J Med Sci Sports*  
764 2015;25(3):301-7.  
765
- 766 37. Malliaropoulos N, Mendiguchia J, Pehlivanidis H, et al. Hamstring exercises for track and  
767 field athletes: injury and exercise biomechanics, and possible implications for exercise  
768 selection and primary prevention. *Br J Sports Med* 2012;46(12):846-51.  
769
- 770 38. Opar DA, Williams MD, Shield AJ. Hamstring strain injuries: factors that lead to injury  
771 and re-injury. *Sports Med* 2012;42(3):209-26.  
772
- 773 39. Gabbe BJ, Branson R, Bennell KL. A pilot randomised controlled trial of eccentric exercise  
774 to prevent hamstring injuries in community-level Australian Football. *J Sci Med Sport*  
775 2006;9(1-2):103-09.  
776
- 777 40. Woodley SJ, Mercer SR. Hamstring muscles: architecture and innervation. *Cells Tissues*  
778 *Organs* 2005;179(3):125-41.  
779

780