Effect of Prior Injury on Changes to Biceps Femoris Architecture across an Australian Football League Season

RYAN G. TIMMINS[1], MATTHEW N. BOURNE[2], JACK T. HICKEY[1], NIRAV MANIAR[1], PAUL J. TOFARI[1], MORGAN D. WILLIAMS[3], and DAVID A. OPAR[1]

[1]School of Exercise Science, Australian Catholic University, Melbourne, AUSTRALIA; [2]Department of Rehabilitation, Nutrition and Sport, La Trobe University Sport and Exercise Medicine Research Centre, Melbourne, Victoria, AUSTRALIA; and [3]School of Health, Sport and Professional Practice, University of South Wales, Pontypridd, Wales, UNITED KINGDOM

ABSTRACT

TIMMINS, R. G., M. N. BOURNE, J. T. HICKEY, N. MANIAR, P. J. TOFARI, M. D. WILLIAMS, and D. A. OPAR. Effect of Prior Injury on Changes to Biceps Femoris Architecture across an Australian Football League Season. *Med. Sci. Sports Exerc.*, Vol. 49, No. 10, pp. 2102–2109, 2017. **Purpose**: To assess in-season alterations of biceps femoris long head (BFlh) fascicle length in elite Australian footballers with and without a history of unilateral hamstring strain injury (HSI) in the past 12 months. **Methods**: Thirty elite Australian football players were recruited. Twelve had a history of unilateral HSI. Eighteen had no HSI history. All had their BFlh architecture assessed at approximately monthly intervals, six times across a competitive season. **Results**: The previously injured limb's BFlh fascicles increased from the start of the season and peaked at week 5. Fascicle length gradually decreased until the end of the season, where they were shortest. The contralateral uninjured limb's fascicles were the longest when assessed at week 5 and showed a reduction in-season where weeks 17 and 23 were shorter than week 1. Control group fascicles were longest at week 5 and reduced in-season. The previously injured limb's BFlh fascicles were shorter than the control group at all weeks and the contralateral uninjured limb at week 5. Compared with the control group, the contralateral uninjured limb had shorter fascicles from weeks 9 to 23. **Conclusions**: Athletes with a history of HSI end the season with shorter fascicles than they start. Limbs without a history of HSI display similar BFlh fascicle lengths at the end of the season as they begin with. All athletes increase fascicle length at the beginning of the season; however, the extent of the increase differed based on history of HSI. These findings show that a HSI history may influence structural adaptation of the BFlh in-season.
Key Words: HAMSTRING, MUSCLE INJURY, FASCICLE LENGTH

For more than 20 years, hamstring strain injuries (HSIs) have been the leading cause of lost playing and training time in elite Australian football (26). Furthermore, HSIs commonly reoccur and typically result in a reduced level of performance after a return to competitive match play (35). These injuries represent a significant financial burden for the athlete and/or their organization (14). Given that a history of HSI has been consistently shown to increase the risk of future HSI (11,25), investigations involving previously injured individuals have attempted to determine if retrospective deficits in structure and/or function of the hamstrings contribute to the elevated risk of reinjury (7,20–23,27,33).

Recently, variations in biceps femoris long head (BFlh) architectural characteristics and their role in the aetiology of HSI have been brought to the attention of researchers and practitioners (30–33). Elite soccer players with shorter BFlh fascicles were reported to have a 4.1-fold increased risk of future HSI, and this was amplified in those athletes with a history of HSI (31). These data, coupled with the finding that a previously injured BFlh consistently displays shorter fascicles than the uninjured contralateral limb (33), suggest that architectural characteristics of those with a history of HSI likely contribute to the elevated rate of reinjury.

Providing interventions for athletes that present with shorter fascicles after ultrasonic examination would appear to be relatively straight forward. This is due to the increasing evidence that resistance exercise, particularly eccentric training targeting the hamstrings, can increase BFlh fascicle length (6,32,34). However, those with a prior HSI might exhibit a reduced scope for positive adaptation as a result of a diminished capacity to activate the previously injured muscle, per the inhibition hypothesis (7,10,22). This reduced ability to activate the previously injured muscle may also limit the extent of strain within the contractile tissue, which in turn may dampen the stimulus needed to increase fascicle length and eccentric strength (4,13,18). One study has examined the

Address for correspondence: Ryan G. Timmins, Ph.D., School of Exercise Science, Australian Catholic University, 115 Victoria Parade, Fitzroy, 3065, Melbourne, Victoria, Australia; E-mail: Ryan.Timmins@acu.edu.au.
Submitted for publication February 2017.
Accepted for publication May 2017.

0195-9131/17/4910-2102/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®
Copyright © 2017 by the American College of Sports Medicine
DOI: 10.1249/MSS.0000000000001333

Copyright © 2017 by the American College of Sports Medicine. Unauthorized reproduction of this article is prohibited.

impact of a prior HSI on the adaptation of the hamstrings, reporting that elite Australian footballers with an HSI in the prior 12 months increased eccentric knee flexor strength to a lesser extent across a preseason training period than individuals without an HSI (24). A restricted capacity to improve eccentric knee flexor strength is at least one mechanism through which prior HSI could increase the risk of future injury (21,31).

Despite the aforementioned findings, it remains unclear as to whether a history of HSI impacts on the adaptive capacity of other risk factors, such as BFlh fascicle length, particularly during the in-season period. It is well established that physical performance variables tend to decline across the in-season period in elite Australian footballers (8). However, it remains to be seen if a specific pathological history might influence these changes. An improved understanding of the in-season changes in BFlh fascicle length, in previously injured and uninjured limbs, may inform on whether those with a history of HSI respond differently to the demands of a competitive season. Such data may have implications for the provision of risk mitigating interventions that are tailored to individuals based on their injury history. Therefore, the purpose of this study was to observe the in-season time course of changes to BFlh architecture in elite Australian footballers, with and without a history of HSI.

METHODS

Participants

In total, 30 males from two clubs in the elite Australian Football League participated in this study. All participants provided written informed consent before collection of any data. For all athletes, team medical staff completed a retrospective injury questionnaire that detailed their history of hamstring, quadriceps, groin, and calf strain injuries and chronic groin pain in the past 12 months, as well as the history of anterior cruciate ligament (ACL) injury at any stage throughout their career. This information was sourced from club medical records via the team doctor or physiotherapist. Of the 30 participants, 18 had no history of HSI or any other significant lower limb injury (including ACL) and formed the control group. Twelve athletes had suffered a unilateral BFlh strain injury in the prior 12 months and formed the previously injured group. Ethical approval for the study was granted by the Australian Catholic University Human Research Ethics Committee (approval number 2016-145E).

Study design. This observational, retrospective cohort study was completed during the 2016 Australian Football League season which consists of 23 wk of competitive matches (March 2016 to August 2016). All participants had their BFlh architecture assessed via two-dimensional ultrasound (Fig. 1) approximately once every month on six separate occasions throughout the in-season period, at a consistent time of day. These assessments occurred at weeks 1, 5, 9, 13, 17, and 23 (final week of competitive games) of the in-season period.

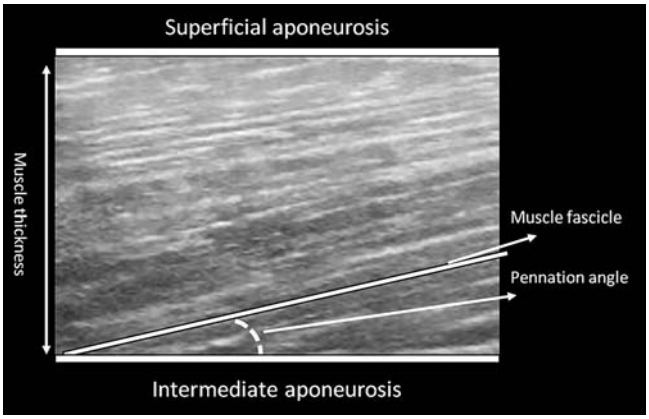

FIGURE 1—A two-dimensional ultrasound image of the BFlh. The image was along the longitudinal axis of the posterior thigh. From these images, it is possible to determine the superficial and intermediate aponeuroses, muscle thickness, and angle of the fascicle in relation to the aponeurosis. Estimates of fascicle length can then be made via trigonometry using an equation validated against cadaveric tissue (5).

BFlh architecture assessment. The protocol for the collection of BFlh muscle architecture has been described previously (29–33). Muscle thickness, pennation angle, and fascicle length of the BFlh were determined from ultrasound images taken along the longitudinal axis of the muscle belly using a two-dimensional, B-mode ultrasound (frequency, 12 MHz; depth, 8 cm; field of view, 14 × 47 mm) (GE Healthcare Vivid-*i,* Wauwatosa, WI). The scanning site was determined as the halfway point between the ischial tuberosity and the knee joint fold, along the line of the BFlh. All architectural assessments were performed with participants in a prone position, with the hip in neutral and the knee fully extended, after at least 5 min of inactivity. To gather ultrasound images, the linear array ultrasound probe, with a layer of conductive gel, was placed on the skin over the scanning site and aligned longitudinally and perpendicular to the posterior thigh. Care was taken to ensure minimal pressure was placed on the skin by the probe. Finally, the orientation of the probe was manipulated slightly by the assessor (R.G.T.) if the superficial and intermediate aponeuroses were not parallel. Reliability of the assessor (R.G.T.) has been previously reported for the assessment of BFlh architectural characteristics (intraclass correlations range from 0.93 to 0.98, and typical error as a percent coefficient of variation range from 2.1 to 3.4) (33). The assessor (R.G.T.) has experience in the assessment of muscle architecture using two-dimensional ultrasound, specifically when assessing the BFlh (6,30–33).

Once the images were collected, analysis was undertaken off-line (MicroDicom, Version 0.7.8, Bulgaria). For each image (Fig. 1), fascicle length estimation was performed as described by Blazevich and colleagues (5). Muscle thickness was defined as the distance between the superficial and intermediate aponeuroses of the BFlh. A fascicle of interest was outlined and marked on the image, and the angle at which

Copyright © 2017 by the American College of Sports Medicine. Unauthorized reproduction of this article is prohibited.

it inserted onto the intermediate aponeurosis was determined as the pennation angle. The superficial and intermediate aponeurosis angles were determined as the angle between the line marked as the aponeurosis and an intersecting horizontal reference line across the captured image (5,16). Because the entire fascicle was not visible in probe's field of view, it was estimated via the following equation from Blazevich and colleagues (5,16):

$$FL = \sin(AA + 90°) \times MT / \sin[180° - (AA + 180° - PA)]$$

where FL, fascicle length; AA, aponeurosis angle; MT, muscle thickness; and PA, pennation angle. Fascicle length was reported in absolute terms (cm) from a single image and fascicle. The same assessor (R.G.T.) collected and analyzed all scans and was blinded to participant identifiers (name, limb and group) during the collection and analysis of the images.

Statistical Analyses

All data (including age, height, and weight) were analyzed using a custom spreadsheet which assessed the magnitude of difference across the season within groups as well as the extent of any between-group differences in muscle architecture, at each time point (15). Because there were no differences between limbs in the control group at all time points, the two-limb averages were used for all comparisons. To reduce bias associated with nonuniformity of error, all data were log-transformed and effect sizes (Cohen *d*) with ±90% confidence interval were calculated. Effect sizes of ≥0.2, ≥0.5, and ≥0.8 were defined as small, moderate and large, respectively, with effect sizes of <0.2 deemed as trivial. Finally, any effects where the 90% confidence interval simultaneously overlapped the positive (≥0.2) and negative (≤−0.2) thresholds of a small effect were defined as being unclear (2).

RESULTS

Power Calculations

Power analysis was undertaken *a priori* using G-Power (9). The analysis was based on anticipated differences in BFlh fascicle length between the injured and contralateral uninjured limbs, using a split-plot ANOVA model. Effect size estimates were based on previous research (33) which reported an effect size of 1.34 when comparing BFlh fascicle length between injured and uninjured limbs. Therefore, an effect size of 1.2 was deemed as a reasonable and conservative starting point for determining sample size. A calculated sample size of 10 per group was determined using the below parameters:

- Power (1 − β err probability) = 0.80
- α = 0.05
- effect size = 1.2

Participant Details

There were no clear differences between the two groups with respect to age (unclear effect; $d = 0.11 \pm 0.60$), height (unclear effect; $d = 0.06 \pm 0.59$), and body mass (unclear effect, $d = 0.26 \pm 0.59$) (previously injured group age, 22.9 ± 2.6 yr; height, 1.87 ± 0.06 m; body mass, 86.0 ± 6.3 kg; control group age, 23.5 ± 3.9 yr; height, 1.88 ± 0.10 m; body mass, 88.7 ± 10.4 kg). Percentage of total time on ground throughout the entire competitive season did not differ between the previously injured (80.6% ± 3.7%) and the control group (79.8% ± 5.4%; unclear effect; $d = 0.17 \pm 0.58$). There were also no within-group differences (example comparison: week 1 vs week 23 in the control group), across the season, in the percentage of total time on ground for either the previously injured (trivial effects: *d* range, 0.15–0.17) or control groups (trivial effects: *d* range, 0.13–0.17).

Throughout the study, three participants suffered a HSI. Two of these were from the control group with the other being from the previously injured group. The injuries for the control group participants occurred between weeks 13 and 17. As a result, these two participants were excluded from analysis at weeks 17 and 23. The previously injured participant's incident occurred after week 23 and was not removed from any analysis due to the injury occurring after the final assessment was completed.

BFlh Architectural Characteristics

Fascicle length. *Temporal changes across the inseason period.* *Previously injured limbs.* Fascicle length in the previously injured limbs increased from week 1 to week 5 (small effect: $d = 0.20 \pm 0.32$) and fascicles were

TABLE 1. Architectural characteristics of the BFlh across a competitive season in elite Australian footballers with and without a history of hamstring strain injury, taken across six time points during the competitive season.

	Previously Injured Group (*n* = 12)						Control Group (*n* = 18)		
	Uninjured Limb			Injured Limb			Two-Limb Average		
Weeks	Muscle Thickness (cm)	Pennation Angle (°)	Fascicle Length (cm)	Muscle Thickness (cm)	Pennation Angle (°)	Fascicle Length (cm)	Muscle Thickness (cm)	Pennation Angle (°)	Fascicle Length (cm)
1	2.72 ± 0.30	14.80 ± 0.82	10.66 ± 1.01	2.63 ± 0.37	14.88 ± 1.08	10.19 ± 0.92	2.82 ± 0.27	14.97 ± 1.03	10.92 ± 0.76
5	2.75 ± 0.25	14.19 ± 0.72	11.18 ± 0.86	2.69 ± 0.32	14.99 ± 0.78	10.41 ± 0.97	2.85 ± 0.26	14.36 ± 0.86	11.48 ± 0.73
9	2.76 ± 0.24	14.92 ± 0.76	10.72 ± 0.80	2.70 ± 0.29	15.13 ± 0.94	10.34 ± 0.92	2.81 ± 0.27	14.40 ± 0.95	11.33 ± 0.77
13	2.74 ± 0.29	15.14 ± 1.12	10.49 ± 0.87	2.66 ± 0.32	15.24 ± 1.28	10.12 ± 1.03	2.83 ± 0.30	14.65 ± 0.98	11.19 ± 0.62
17	2.70 ± 0.28	15.10 ± 1.30	10.38 ± 0.92	2.64 ± 0.36	15.22 ± 1.30	10.05 ± 1.15	2.76 ± 0.29	14.68 ± 1.11	10.87 ± 0.77
23	2.72 ± 0.28	15.59 ± 1.30	10.18 ± 0.79	2.72 ± 0.37	16.42 ± 1.07	9.53 ± 1.20	2.81 ± 0.30	15.26 ± 0.97	10.62 ± 0.71

Data presented as mean ± SD.

Copyright © 2017 by the American College of Sports Medicine. Unauthorized reproduction of this article is prohibited.

TABLE 2. Within-group effect size (±90% CI) changes of BFlh fascicle length across a competitive season in elite Australian footballers.

	Injured					Contralateral Uninjured					Control				
Weeks	5	9	13	17	23	5	9	13	17	23	5	9	13	17	23
1	$0.20^{a} \pm 0.32$	0.14 ± 0.39	-0.08 ± 0.50	-0.06 ± 0.60	$-0.56^{b} \pm 0.62$	$0.47^{a} \pm 0.27$	0.07 ± 0.29	-0.14 ± 0.29	$-0.38^{a} \pm 0.32$	$-0.39^{a} \pm 0.41$	$0.67^{b} \pm 0.33$	$0.50^{b} \pm 0.38$	$0.34^{a} \pm 0.37$	-0.04 ± 0.37	-0.33 ± 0.56
5		-0.06 ± 0.21	$-0.28^{a} \pm 0.29$	$-0.31^{a} \pm 0.34$	$-0.75^{b} \pm 0.37$		$-0.40^{a} \pm 0.20$	$-0.62^{b} \pm 0.28$	$-0.81^{c} \pm 0.40$	$-0.89^{c} \pm 0.35$		-0.17 ± 0.22	$-0.33^{a} \pm 0.23$	$-0.73^{b} \pm 0.31$	$-1.01^{c} \pm 0.31$
9			$-0.22^{a} \pm 0.15$	$-0.29^{a} \pm 0.21$	$-0.64^{b} \pm 0.27$			$-0.21^{a} \pm 0.19$	$-0.35^{a} \pm 0.30$	$-0.50^{b} \pm 0.27$			-0.16 ± 0.19	$-0.53^{b} \pm 0.33$	$-0.84^{c} \pm 0.41$
13				-0.05 ± 0.15	$-0.40^{a} \pm 0.23$				-0.14 ± 0.19	$-0.22^{a} \pm 0.17$				$-0.39^{a} \pm 0.24$	$-0.72^{b} \pm 0.34$
17					$-0.37^{a} \pm 0.15$					-0.17 ± 0.21					$-0.42^{a} \pm 0.26$

Athletes with a unilateral history of HSI are represented by the previously injured and contralateral uninjured limbs. The control group data is the two limb average of athletes without a history of HSI.
All other effect size changes were unclear or trivial.
[a]Small effect size for comparison.
[b]Moderate effect size for comparison.
[c]Large effect size for comparison.

longer at all time points when compared with week 23 (small to moderate effects; *d* range: 0.22–0.75; Tables 1 and 2, Fig. 2). Furthermore, fascicles were longer at weeks 5 and 9 compared with weeks 13 and 17 (small effect; *d* range = 0.22–0.31; Tables 1 and 2, Fig. 2)

Contralateral uninjured limbs. Fascicle length was longest at week 5 compared with all other weeks (small to large effects; *d* range = 0.40–0.89; Tables 1 and 2, Fig. 2). Furthermore, fascicle lengths were longer at weeks 1 and 9 compared with weeks 17 and 23 (small to moderate effects; *d* range = 0.35–0.50; Tables 1 and 2, Fig. 2). Week 9 also displayed longer fascicles compared with week 13 (small effect; $d = 0.21 \pm 0.19$; Tables 1 and 2, Fig. 2), whereas at week 13, fascicles were longer compared with week 23 (small effect; $d = 0.22 \pm 0.17$; Tables 1 and 2, Fig. 2).

Control group. Longer fascicles were observed in the control group at weeks 5, 9, and 13 when compared with weeks 1, 17, and 23 (small to large effects; *d* range, 0.34–1.01; Tables 1 and 2, Fig. 2). Furthermore, fascicles were longer at week 5 compared with week 13 (small effect; $d = 0.33 \pm 0.23$; Tables 1 and 2, Fig. 2) and longer at week 17 compared with week 23 (small effect; $d = 0.42 \pm 0.26$; Tables 1 and 2, Fig. 2).

Between-group comparisons. *Previously injured limbs compared with contralateral uninjured limb*. The previously injured limb displayed shorter fascicle lengths compared with the contralateral uninjured limb only at week 5 (moderate effect; $d = -0.76 \pm 0.68$; Table 3).

Previously injured limbs compared with control group. Fascicle length of the previously injured limb was shorter than the control group at all time points (moderate to large effects; *d* range: −1.15 to −0.77; Table 3).

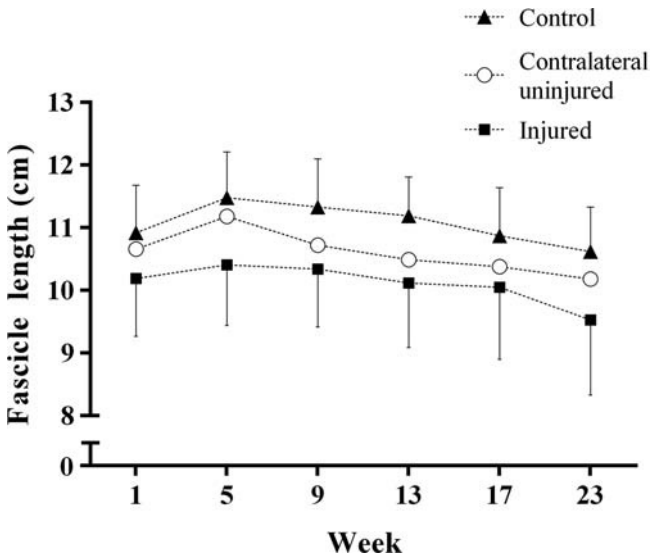

FIGURE 2—Fascicle length changes of the BFlh in previously hamstring strain injured limbs, the contralateral uninjured limb and two-limb average of the control group without a history of hamstring strain injury from elite Australian footballers. The weeks are each separated by approximately 28 d, and all data were collected during the in-season period. Error bars represent SD.

Copyright © 2017 by the American College of Sports Medicine. Unauthorized reproduction of this article is prohibited.

TABLE 3. Between-group effect size (±90% CI) changes of BFlh architectural characteristics across a competitive season in elite Australian footballers.

	Contralateral Uninjured Limb Minus Previously Injured Limb			Control Group Average Minus Contralateral Uninjured Limb			Control Group Average Minus Previously Injured Limb		
Week	Muscle Thickness	Pennation Angle	Fascicle Length	Muscle Thickness	Pennation Angle	Fascicle Length	Muscle Thickness	Pennation Angle	Fascicle Length
1	0.28 ± 0.68	−0.06 ± 0.68	0.45 ± 0.68	0.32 ± 0.64	0.16 ± 0.60	0.29 ± 0.64	0.56 ± 0.65[b]	0.08 ± 0.62	0.81 ± 0.64[c]
5	0.20 ± 0.68	−1.04 ± 0.68[c]	0.76 ± 0.68[b]	0.33 ± 0.62	0.21 ± 0.61	0.35 ± 0.63	0.48 ± 0.64[a]	−0.76 ± 0.61[b]	1.11 ± 0.65[c]
9	0.22 ± 0.68	−0.22 ± 0.68	0.42 ± 0.68	0.18 ± 0.61	−0.61 ± 0.60[b]	0.72 ± 0.63[c]	0.38 ± 0.63	−0.75 ± 0.61[b]	1.09 ± 0.64[c]
13	0.26 ± 0.68	−0.09 ± 0.68	0.38 ± 0.68	0.29 ± 0.62	−0.46 ± 0.62[a]	0.87 ± 0.64[b]	0.53 ± 0.63[c]	−0.50 ± 0.63[b]	1.15 ± 0.65[c]
17	0.15 ± 0.76	0.00 ± 0.77	0.21 ± 0.76	0.21 ± 0.67	−0.33 ± 0.67	0.54 ± 0.68[c]	0.36 ± 0.69	−0.42 ± 0.67	0.77 ± 0.70[b]
23	−0.07 ± 0.70	−0.61 ± 0.69[b]	0.43 ± 0.71	0.31 ± 0.64	−0.29 ± 0.66	0.60 ± 0.65[c]	0.16 ± 0.66	−1.01 ± 0.63[b]	0.89 ± 0.68[c]

Athletes with a unilateral history of HSI are represented by the previously injured and contralateral uninjured limbs. The control group data is the two limb average of athletes without a history of HSI.
All other effect size changes were unclear or trivial.
[a]Small effect size for comparison.
[b]Moderate effect size for comparison.
[c]Large effect size for comparison.

Contralateral uninjured limb compared with control group. The contralateral uninjured limb displayed shorter fascicles compared with the control group average at weeks 9, 13, 17, 23 (moderate to large effect; d range = −0.87 to −0.54; Table 3).

Pennation angle. *Temporal changes across the in-season period.* *Previously injured limbs.* Pennation angle in the previously injured limb was smaller at all weeks compared with week 23 (moderate to large effects; d = −1.13 to −0.60, Table 1). Pennation angle was also lesser at week 5 compared with week 17 (small effect; d = 0.26 ± 0.44, Table 1).

Contralateral uninjured limb. Pennation angle was less at week 5 compared with all other weeks (moderate to large effect; d range = −1.61 to −0.71, Table 1). In contrast, pennation angle was larger at week 23 compared with all other time points (small to large effects; d range = 0.35–1.61, Table 1). Pennation angle was also lesser at week 1 compared with week 13 (small effect; d = 0.36 ± 0.50, Table 1).

Control group. Pennation angle was greatest at weeks 1 and 23 when compared with all other weeks (small to large effects; d range = 0.21 to 0.94, Table 1). Further, pennation angle was greater at weeks 13 and 17 when compared with weeks 5 and 9 (small effects; d range = 0.23–0.33, Table 1).

Between-group comparisons. *Previously injured limbs compared with contralateral uninjured limb.* Pennation angle in the previously injured limb was larger compared with the contralateral uninjured limbs at weeks 5 and 23 (moderate to large effects; d range = 0.61–1.04; Table 3).

Previously injured limbs compared with control group. When compared with the control group, previously injured limbs had greater pennation angles at weeks 5, 9, 13, and 23 (moderate to large effects; d range = 0.50–1.01; Table 3).

Contralateral uninjured limb compared with control group. The contralateral uninjured limb's pennation angle was greater than the control group average at week 9 (d = 0.61 ± 0.60) and 13 (d = 0.46 ± 0.62).

Muscle thickness. *Temporal changes across the in-season period.* *Previously injured limbs.* Muscle thickness was greater at week 23 compared with week 1 (small effect; d = 0.26 ± 0.45, Table 1).

Contralateral uninjured limb. No small, moderate or large effects were detected for muscle thickness across all time points.

Control group. Muscle thickness was greater at week 5 (d = 0.29 ± 0.19, Table 1) and week 13 (d = 0.20 ± 0.13, Table 1) compared with week 17.

Between-group comparisons. *Previously injured limbs compared with contralateral uninjured limb.* No small, moderate or large effects were detected for muscle thickness between the previously injured and uninjured contralateral limbs.

Previously injured limbs compared with control group. Compared with the control group the previously injured limbs had lesser muscle thickness at weeks 1, 5, and 13 (moderate effect; d range −0.56 to −0.48; Table 3).

Contralateral uninjured limb compared with control group. No small, moderate or large effects were detected.

DISCUSSION

The main findings of this study were 1) those with a history of unilateral HSI end the in-season period with shorter BFlh fascicles compared with the start of the in-season period in both their previously injured and contralateral uninjured limb; 2) uninjured limbs display similar BFlh fascicle lengths at the start of the in-season period compared with the end of the in-season period; and 3) increases in BFlh fascicle length were observed early in-season across all athletes; however, the magnitude of this increase differed based on history of HSI.

BFlh fascicle length has been identified as a modifiable risk factor for HSI (31); however, it was previously unclear as to how or if this parameter changed across a season in elite Australian footballers. In the current study, all groups increased BFlh fascicle length during the early part of the in-season period, which then progressively shortened until the end of the competitive season. Of note, the increase was largest in the control group (moderate effect, d = 0.67 ± 0.33), followed by the contralateral uninjured limbs (small

Copyright © 2017 by the American College of Sports Medicine. Unauthorized reproduction of this article is prohibited.

effect, $d = 0.47 \pm 0.27$) and finally the previously injured limbs (small effect, $d = 0.20 \pm 0.32$). This divergence in early in-season responses across groups appears to be a factor that ultimately results in both limbs from the previously injured athlete possessing shorter fascicles at the conclusion of the season compared with the start of the season. From weeks 5 to 23, the control group displays the largest decline in fascicle length (large effect, $d = -1.01 \pm 0.31$), followed by the contralateral uninjured limbs (large effect, $d = -0.89 \pm 0.35$) and then the previously injured limbs (moderate effect, $d = -0.75 \pm 0.37$). These findings differ to work which has examined in-season alterations in vastus lateralis fascicle length, in softball and track and field (3,19). In these studies, an initial decline in the first half of the competitive season was counteracted by an increase at the end of the season (3,19). However, as the vastus lateralis acts in an antigravity nature, it is likely that the differing roles of the knee extensors and flexors contribute to these divergent findings, as would the differing demands between the sports examined.

The current data suggest that the early in-season period (i.e., within the first 1 to 2 months of the commencement of the season) may be an important time to continue to implement interventions to increase BFlh fascicle length, particularly in Australian footballers with a history of HSI. Simplistically, there is the possibility that this could be achieved with high-intensity, eccentric loading strategies that can elicit favorable adaptations within 2 wk (32). However, there are likely a number of practical considerations that may limit or preclude such a strategy in elite sporting environments compared with those observed from laboratory-based studies in recreational athletes. These may include coach/athlete apprehension toward eccentrically induced muscle damage often reported in response to unaccustomed training (1) (which can be accentuated by the extent of the muscle strain undertaken during lengthening contractions [17]). Also, a greater emphasis placed on recovery between matches at the expense of loading exposures (12,28), as well as the presence or accumulation of other lower limb injuries that might not result in on-field time loss but do require modifications to resistance exercise prescription. Prior evidence has suggested that the detraining effect for BFlh fascicles after eccentric training interventions can occur in as little as 4 wk (32), which would justify the need for constant application of an eccentric strength training stimulus, yet implementation appears to be challenging in practice (1).

It should be acknowledged that the current study is limited because no architecture data was captured during the preseason period, which spans November to February. It is certainly possible that the previously injured athletes increased fascicle length substantially during this period, and future work should seek to explore this possibility. Nevertheless, across the entire in-season period, the previously injured hamstrings possessed shorter fascicles than the control group at all weeks (moderate to large effects throughout). These findings are likely to at least partly explain the high rates of HSI recurrence seen in Australian footballers (26). Therefore, consideration should be given to what previously injured Australian footballers are capable of doing during their off-season program as a means of minimizing any deficits at the commencement of the season. As exposure to high-speed running can be minimized in the off-season, this may allow for the application of high-intensity strength training interventions targeted at increasing or at least minimizing reductions in BFlh fascicle length, leading into the next preseason and in-season periods.

The current study indirectly infers the possibility that previously injured athletes/limbs are less capable of adapting positively to the rigours of in-season demands compared with those without a history of injury. Similar observational research has found that previously injured Australian footballers display less improvement in eccentric knee flexor strength across the preseason compared with their uninjured counterparts (24). Such limited adaptation in previously injured athletes could be partly attributed to prolonged neuromuscular inhibition (10), which has been noted in previously injured athletes even after returning to preinjured levels of competition (7,22,23,33). For example, a previously injured BFlh has been shown to be significantly less active than uninjured contralateral muscles during performance of the Nordic hamstring curl (7), which is an exercise commonly used in HSI rehabilitation (35). It is possible that this limited activation may result in a reduced amount of strain within the tissue and limit the stimulus required to increase fascicle length (4,13). However, from a mechanistic perspective, this phenomenon requires further investigation. No study has investigated whether individuals with and without a prior history of HSI respond differently to controlled interventions aimed at increasing eccentric strength and fascicle length. Should differences exist, further exploration as to whether inhibition manifests at the spinal or supraspinal level would be necessary to guide interventions targeted at restoring voluntary activation capacity after injury.

The authors acknowledge there are limitations in the current study. First, there are methodological limitations with the use of two-dimensional ultrasound to estimate BFlh fascicle length. As the fascicles which were measured are longer than the field of view which was used, the entire fascicle was not captured. Therefore, estimation was required to determine BFlh fascicle length. The estimation process used has been previously validated against cadaveric samples (5,16). However, it must be recognized that there is still error associated with the determination of BFlh fascicle length (in this assessment typical error is approximately 0.30 cm). Second, there was no concurrent collection of match and training exposure, internal and external training load and resistance training programming variables. As several factors are likely modulators of fascicle length, examining the interaction between previous injury status and the aforementioned variables needs to be the focus of the next series of studies in this area.

Copyright © 2017 by the American College of Sports Medicine. Unauthorized reproduction of this article is prohibited.

CONCLUSIONS

Elite Australian footballers with a history of HSI display shorter BFlh fascicles at the completion of the season compared with the start, in both their injured and uninjured limbs. In contrast, athletes without a history of HSI finish the season with similar fascicle lengths to what they started with. All athletes experience lengthening of BFlh fascicles shortly after the commencement of the season which was followed by a sustained period of shortening for the rest of the season. The impact of injury history on the structural and functional adaptations of the hamstrings requires further examination, to assist practitioners and clinicians to develop novel strategies to mitigate the risk of recurrent HSI in their athletes.

The authors would like to thank Dr Anthony Schache, Mr Christopher Howley and Mr James Rance for their assistance with participant recruitment and compliance throughout the project.

Conflict of Interest: The authors wish to disclose that there were no conflicts of interest associated with professional relationships, that the study does not constitute endorsement by ACSM, and that the results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. This study was unfunded.

REFERENCES

1. Bahr R, Thorborg K, Ekstrand J. Evidence-based hamstring injury prevention is not adopted by the majority of Champions League or Norwegian Premier League football teams: the Nordic Hamstring survey. *Br J Sports Med*. 2015;49(22):1466–71.
2. Batterham AM, Hopkins WG. Making meaningful inferences about magnitudes. *Int J Sports Physiol Perform*. 2006;1(1):50–7.
3. Bazyler CD, Mizuguchi S, Harrison AP, et al. Changes in muscle architecture, explosive ability, and track and field throwing performance throughout a competitive season and following a taper. *J Strength Cond Res*. 2016; Epub ahead of print. doi: 10.1519/JSC.0000000000001619.
4. Best TM, McElhaney JH, Garrett WE Jr, Myers BS. Axial strain measurements in skeletal muscle at various strain rates. *J Biomech Eng*. 1995;117(3):262–5.
5. Blazevich AJ, Gill ND, Zhou S. Intra- and intermuscular variation in human quadriceps femoris architecture assessed in vivo. *J Anat*. 2006;209(3):289–310.
6. Bourne MN, Duhig SJ, Timmins RG, et al. Impact of the Nordic hamstring and hip extension exercises on hamstring architecture and morphology: implications for injury prevention. *Br J Sports Med*. 2017;51(5):469–77.
7. Bourne MN, Opar DA, Williams MD, Al Najjar A, Shield AJ. Muscle activation patterns in the Nordic hamstring exercise: Impact of prior strain injury. *Scand J Med Sci Sports*. 2016;26(6):666–74.
8. Cormack SJ, Newton RU, McGuigan MR, Cormie P. Neuromuscular and endocrine responses of elite players during an Australian rules football season. *Int J Sports Physiol Perform*. 2008;3(4):439–53.
9. Faul F, Erdfelder E, Lang AG, Buchner A. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav Res Methods*. 2007;39(2):175–91.
10. Fyfe JJ, Opar DA, Williams MD, Shield AJ. The role of neuromuscular inhibition in hamstring strain injury recurrence. *J Electromyogr Kinesiol*. 2013;23(3):523–30.
11. Gabbe BJ, Bennell KL, Finch CF, Wajswelner H, Orchard JW. Predictors of hamstring injury at the elite level of Australian football. *Scand J Med Sci Sports*. 2006;16(1):7–13.
12. Gabbett TJ, Whiteley R. Two training-load paradoxes: can we work harder and smarter, can physical preparation and medical be team-mates? *Int J Sports Physiol Perform*. 2016;13:1–16.
13. Garrett WE Jr, Safran MR, Seaber AV, Glisson RR, Ribbeck BM. Biomechanical comparison of stimulated and nonstimulated skeletal muscle pulled to failure. *Am J Sports Med*. 1987;15(5):448–54.
14. Hickey J, Shield AJ, Williams MD, Opar DA. The financial cost of hamstring strain injuries in the Australian Football League. *Br J Sports Med*. 2014;48(8):729–30.
15. Hopkins WG. Spreadsheets for analysis of controlled trials, with adjustment for a predictor. *Sportscience*. 2006;10:46–50.
16. Kellis E, Galanis N, Natsis K, Kapetanos G. Validity of architectural properties of the hamstring muscles: correlation of ultrasound findings with cadaveric dissection. *J Biomech*. 2009;42(15):2549–54.
17. Lieber RL, Fridén J. Muscle damage is not a function of muscle force but active muscle strain. *J Appl Physiol (1985)*. 1993;74(2):520–6.
18. Liu H, Garrett W, Moorman C, Yu B. Injury rate, mechanism, and risk factors of hamstring strain injuries in sports: a review of the literature. *J Sport Health Sci*. 2012;1(2):92–101.
19. Nimphius S, McGuigan MR, Newton RU. Changes in muscle architecture and performance during a competitive season in female softball players. *J Strength Cond Res*. 2012;26(10):2655–66.
20. Opar DA, Piatkowski T, Williams MD, Shield AJ. A novel device using the nordic hamstring exercise to assess eccentric knee flexor strength: a reliability and retrospective injury study. *J Orthop Sports Phys Ther*. 2013;43(9):636–40.
21. Opar D, Williams M, Timmins R, Hickey J, Duhig S, Shield A. Eccentric hamstring strength and hamstring injury risk in Australian Footballers. *Med Sci Sports Exerc*. 2015;47(4):857–65.
22. Opar DA, Williams MD, Timmins RG, Dear NM, Shield AJ. Knee flexor strength and bicep femoris electromyographical activity is lower in previously strained hamstrings. *J Electromyogr Kinesiol*. 2013;23(3):696–703.
23. Opar DA, Williams MD, Timmins RG, Dear NM, Shield AJ. Rate of torque and electromyographic development during anticipated eccentric contraction is lower in previously strained hamstrings. *Am J Sports Med*. 2013;41(1):116–25.
24. Opar DA, Williams MD, Timmins RG, Hickey J, Duhig SJ, Shield AJ. The effect of previous hamstring strain injuries on the change in eccentric hamstring strength during preseason training in elite Australian footballers. *Am J Sports Med*. 2015;43(2):377–84.
25. Orchard JW. Intrinsic and extrinsic risk factors for muscle strains in Australian football. *Am J Sports Med*. 2001;29(3):300–3.
26. Orchard JW, Seward H, Orchard JJ. Results of 2 decades of injury surveillance and public release of data in the Australian Football League. *Am J Sports Med*. 2013;41(4):734–41.
27. Sole G, Milosavljevic S, Nicholson HD, Sullivan SJ. Selective strength loss and decreased muscle activity in hamstring injury. *J Orthop Sports Phys Ther*. 2011;41(5):354–63.
28. Soligard T, Schwellnus M, Alonso JM, et al. How much is too much? (Part 1) International Olympic Committee consensus statement on load in sport and risk of injury. *Br J Sports Med*. 2016;50(17):1030–41.
29. Timmins R. Biceps femoris architecture: the association with injury and response to training. *Br J Sports Med*. 2017;51:547–8.
30. Timmins RG, Bourne MN, Shield AJ, Williams MD, Lorenzen C, Opar DA. Biceps femoris architecture and strength in athletes with

Copyright © 2017 by the American College of Sports Medicine. Unauthorized reproduction of this article is prohibited.

a previous anterior cruciate ligament reconstruction. *Med Sci Sports Exerc*. 2016;48(3):337–45.
31. Timmins RG, Bourne MN, Shield AJ, Williams MD, Lorenzen C, Opar DA. Short biceps femoris fascicles and eccentric knee flexor weakness increase the risk of hamstring injury in elite football (soccer): a prospective cohort study. *Br J Sports Med*. 2016;50(24): 1524–35.
32. Timmins RG, Ruddy JD, Presland J, et al. Architectural changes of the biceps femoris long head after concentric or eccentric training. *Med Sci Sports Exerc*. 2016;48(3):499–508.
33. Timmins R, Shield A, Williams M, Lorenzen C, Opar D. Biceps femoris long head architecture: a reliability and retrospective injury study. *Med Sci Sports Exerc*. 2015;47(5):905–13.
34. Timmins RG, Shield AJ, Williams MD, Lorenzen C, Opar DA. Architectural adaptations of muscle to training and injury: a narrative review outlining the contributions by fascicle length, pennation angle and muscle thickness. *Br J Sports Med*. 2016;50(23):1467–72.
35. Verrall GM, Kalairajah Y, Slavotinek JP, Spriggins AJ. Assessment of player performance following return to sport after hamstring muscle strain injury. *J Sci Med Sport*. 2006;9(1–2):87–90.

Copyright © 2017 by the American College of Sports Medicine. Unauthorized reproduction of this article is prohibited.