Nonuniform Changes in MRI Measurements of the Thigh Muscles After Two Hamstring Strengthening Exercises

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Abstract

Mendiguchia, J, Garrues, MA, Cronin, JB, Contreras, B, Los Arcos, A, Malliaropoulos, N, Maffulli, N, and Idoate, F. Nonuniform changes in MRI measurements of the thigh muscles after two hamstring strengthening exercises. *J Strength Cond Res* 27(3): 574–581, 2013. Although many different hamstring strengthening exercises exist, the effect on site specific activation of these exercises on different muscles of the leg is unclear. This study investigated the effects of the eccentric leg curl (LC) and lunge (L) exercises on the biceps femoris long head (BFl), biceps femoris short head (BFs), semitendinosus (ST), semimembranosus (SM), and adductor magnus (AM). Each leg of 11 male professional soccer players was randomly assigned to an LC or L exercise protocol (3 sets of 6 repetitions). Functional magnetic resonance imaging (fMRI) of the subjects' thighs were performed before and 48 hours after the intervention. Fifteen axial scans of the thigh interspaced by a distance of 1/15 right femur length (L_f) were obtained. The fMRI data were analyzed for signal intensity changes. No significant changes were observed in absolute short tau inversion recovery values for the SM and BFs. Significant changes for the ST (~21–45%) from sections 4 to 10, AM (~2–13%) at section 4, and BFl (~ −3 vs. 8%) at section 7 were noted. LC exercises load all the regions of the ST muscle. The L exercises load the proximal regions of the BFl and AM. These findings may have relevance when designing protocols for prevention and rehabilitation of hamstring injuries.

Key Words eccentric exercise, injury prevention, hamstring rehabilitation

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Introduction

Acute hamstring injuries are the most prevalent muscle injuries in sport, accounting for 6–37% of all injuries reported in Australian Rules football, rugby union, soccer, basketball, cricket, and track sprinters (6,7,10,12,29,35,47). Nearly one-third of these injuries recur within the first year after a return to sport, with subsequent injuries often being more severe than the original (38). Eccentric strengthening of the hamstring muscles has been recommended as a key component in the management of hamstring injury (3,11,19,22,31). Eccentric training has the ability to increase the size and strength of muscles with very little demand on the cardiovascular system while at the same time altering some muscle mechanical properties such as optimum length and muscle stiffness (30). It seems that these effects can be achieved through eccentric exercises that actively lengthen the hamstrings with hip flexion, knee extension, or a combination of both.

Current approaches to hamstring strengthening have been guided by knowledge of the anatomy and function of the muscles constituting the hamstrings: the long head of the biceps femoris muscle (BFl), the short head of the biceps femoris (BFs), the semimembranosus (SM), and the semitendinosus (ST). The architecture and innervation patterns of the various muscles differ (15,45,46), and it is likely that each muscle has unique functions. If this is indeed the case, it would be of value to strength and conditioning coaches and clinicians to understand which exercises preferentially activate different muscle groups, so as to better guide conditioning and rehabilitation programs.

Functional magnetic resonance imaging (fMRI) may be used as a sensitive, noninvasive method to display the physiological changes that occur in muscles activated during exercise, because it provides detailed anatomical analysis of associated soft tissues, which is lacking in electromyography experiments (4,16,20,24,25,42). The short tau inversion recovery (STIR) sequence is a T2-weighted sequence that suppresses signals from fat, and a display enhances differences between the water content of tissues (4,16,24,42). Exercise produces changes in the distribution of water both intracellularly and intercellularly. The STIR sequence is valuable in the investigation of signal intensity (SI) changes in muscles after exercise (4,16,24,42). The fMRI has also been used to assess muscle damage after intensive exercise (8,28). The T2 values increase after eccentric exercise (21,25,27,37,39,40,47) and T2 values are positively correlated with plasma creatine kinase (CK) activity, reflecting exercise-induced muscle damage (24,25,37). There are intermuscle differences and intramuscle regional differences in T2 values between proximal and distal regions of the hamstring muscles of interest (2,24,25,38). For example, although all hamstring muscles and regions displayed a T2 increase immediately after eccentric knee-flexion exercise (prone leg-curl machine), the relationship between the changes in plasma CK activity and T2 value of the ST was not statistically significant until the second day after exercise, which may be indicative of severe localized muscle damage (25). These findings have interesting implications in terms of the time course and effects of different exercises on the hamstrings.

Despite the on-going use of certain eccentric exercises in preventing hamstring injuries among elite athletes (3,11,19,22,31), fMRI, to our knowledge, has not been used to investigate muscle damage and intermuscle and intramuscle regional differences in STIR values. The aim of this study was to assess SI changes in the upper thigh muscles using fMRI at 48 hours after a lunge (L) and eccentric leg-curl exercises (LC). The information derived from this investigation should enable the clinician, strength and conditioning coach, and physiotherapist to have a better understanding of site-specific activation of the posterior thigh muscles, which in turn should guide better practices in injury prevention, rehabilitation, and selective strengthening of the hamstrings muscles.

Methods

Experimental Approach to the Problem

This study evaluated the hypothesis that different hamstring muscle exercises (L and LC) target different posterior thigh muscles and locations. Thus, the fMRI of the thigh was performed at different length sections (2,5,7,9,13,16) of muscles BFl, BFs, SM, ST, and adductor magnus (AM), before and after eccentric exercise. The subjects randomly perform an eccentric leg curl (LC) or lunge (L) with the left or right leg. After the completion of the exercise protocol for 1 leg (e.g., LC), the subjects started the second exercise for the other leg (e.g., L).

Subjects

Eleven male professional soccer players from the same football team were invited to participate in this study at the end of the season, when minimal training and no competition were undertaken. The participants were excluded if they had an injury to their legs or back in the preceding 12 months or if they were unsuitable for fMRI because of metallic foreign bodies, electronic implants, or claustrophobia. Before the start of the investigation, each participant's height, weight, age, regular exercise program and any previous injuries to the legs were recorded (Table 1). The subjects were instructed to avoid strength-training activities for the lower legs and to not use icing or anti-inflammatory medication for the week preceding and the week of the experiment; they were also encouraged to keep a diet and fluid intake diary. Our institutional Ethics Committee approved the study, and all the participants gave written informed consent to participate in the study.

Exercise Protocol

The left and right legs of each subject were randomly assigned from an independent researcher not involved in this study to an LC or L exercise protocol. The protocol involved 3 sets of 6 repetitions with at least a 2-minute rest between sets. After the completion of the exercise protocol for 1 leg (e.g., LC), a 2-minute rest was taken before starting the second exercise (e.g., L) for the other leg.

Procedure

For the L exercise, the subjects were instructed to step forward a predetermined distance marked on the floor while the trunk remained upright. The length of the step was standardized for each subject and was equal to the distance from the greater trochanter to the floor as measured with the subject in standing position. The subjects were asked to step forward by flexing their lead and trailing knees simultaneously to a point where the trail knee was approximately 2–3 cm short of contacting the ground. The lunge was completed when the subjects returned to the starting position.

Table 1. General initial characteristics of subjects (mean ± *SD*).

	n	Mean	*SD*
Height (m)	11	1.80	0.05
Weight (kg)	11	74.59	4.52
Age (y)	11	22.09	1.79

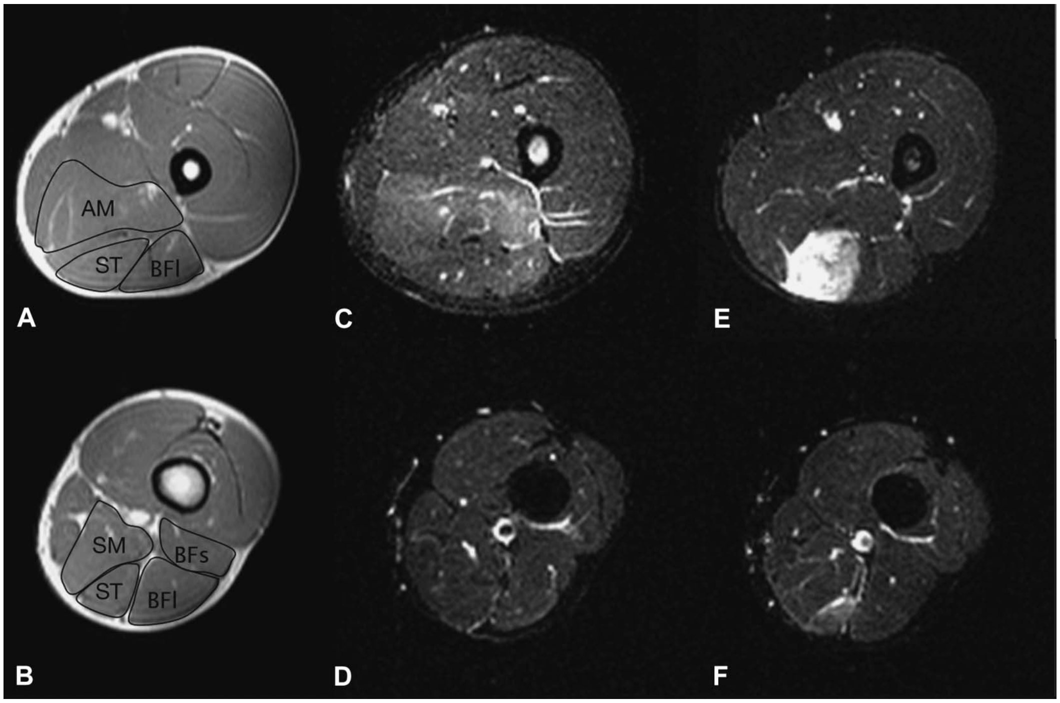

Figure 1. Representative DP-weighted (A, B) and short tau inversion recovery (STIR) magnetic resonance images of the thigh at L_f 7 (first row A–C) and L_f 10 (lower rows E, F) obtained after lunge (B, D) and eccentric leg-curl (E, F) exercise protocols. Note that at proximal thigh adductor magnus (AM) and biceps femoris long head (BFl) are brightened after lunge exercise (C), and semitendinous (ST) after eccentric leg curl (E). At distal thigh ST shows increased signal intensity after eccentric leg-curl exercise. Semimembranosus and biceps femoris short head (BFs) muscles show no increased signal intensity.

For the LC exercise, the subjects performed eccentric hamstring curls (Prone Leg Curl Technogym, Italy) at 120% of their 1-repetition maximum (1RM). The LC 1RM was determined using an incremental load to failure protocol. Once the subject could not complete 2 concentric LCs at the set load, this was considered as their 1RM to which a 20% load was added, which resulted in the 120% 1RM eccentric load. The subjects were instructed to lower the weight from a knee-flexed position (100°) to a knee-extended position (0°) in 3 seconds, maintaining a constant lowering speed. The subjects plantar-flexed their ankles to reduce the contribution of the gastrocnemius muscle. The subjects were verbally encouraged to produce maximal force at the starting position and to resist maximally against the knee-extending action throughout the range of motion. The weight was raised after each eccentric repetition by an examiner, thereby making the exercise an eccentric-only task for the subject.

Imaging Technique

All fMRI of the thigh were performed using a 1-T whole-body imager (Magnetom Impact Expert; Siemens-Erlangen, Germany). For the fMRI scans, the subjects were positioned supine with their knees extended. All the scans were performed immediately before and 48 hours after the exercise. Once the subjects were positioned inside the magnet, the thighs of both legs were kept parallel to the fMRI table, and the feet were strapped together to prevent rotation. The length of the right femur (L_f), taken as the distance from the intercondylar notch of the femur to the superior aspect of the femoral head, was measured in the coronal plane.

Subsequently, 15 axial scans of the thigh interspaced by a distance of $1/15L_f$ were obtained from the level of $1/15L_f$ to $15/15L_f$. Every image obtained was labeled at its location (i.e., slice 4 being closer to the coxofemoral joint and slice 12 closer to the knee). Great care was taken to reproduce the same individual L_f each time by using the appropriate anatomical landmarks (17). For the final calculation of the SI of each muscle, slices 4/15–12/15 were used for all muscles examined; the 2 cranial slices (closer to the hip), and the 3 distal slices (closer to the knee) were discarded given the presence of image artifacts. Then, fast STIR magnetic resonance axial images (repetition time = 5,300 milliseconds, echo time = 60 milliseconds, inversion time = 115 milliseconds, flip angle = 180) were collected using a 256 × 256 image matrix, with a 350-mm field of view and 10-mm slice thickness using a body coil.

The fMRI data of all posterior thigh muscles (BFl, BFs, SM, ST, and AM) represented in each axial scan section

Table 2. STIR absolute values (mean ± *SD*) of muscles before and after exercise for lunge and leg-curl exercise.*†

LC					L					
Muscle and section	Time	*n*	Mean ± *SD*	*t*-Test *p*	Muscle and section	Time	*n*	Mean ± *SD*	*t*-Test *p*	ANOVA RM *p*
ST4	Before	11	128.09 ± 15.33	*0.048*	ST4	Before	11	133.36 ± 12.99	0.718	*0.033*
	After	11	189.00 ± 89.37			After	11	131.00 ± 14.35		
ST5	Before	11	134.45 ± 10.71	*0.021*	ST5	Before	11	132.27 ± 12.26	0.068	*0.019*
	After	11	267.36 ± 165.25			After	11	139.91 ± 13.45		
ST6	Before	11	146.27 ± 20.70	*0.005*	ST6	Before	11	132.00 ± 15.06	0.057	*0.004*
	After	11	342.45 ± 186.45			After	11	143.73 ± 17.97		
ST7	Before	11	135.91 ± 18.66	0.007	ST7	Before	11	126.27 ± 15.92	0.085	*0.005*
	After	11	321.45 ± 183.13			After	11	136.27 ± 16.43		
ST8	Before	11	130.73 ± 17.82	*0.016*	ST8	Before	11	124.36 ± 12.87	*0.028*	*0.018*
	After	11	234.64 ± 115.64			After	11	134.73 ± 16.06		
ST9	Before	10	131.80 ± 14.70	0.054	ST9	Before	10	126.20 ± 15.16	0.696	*0.048*
	After	10	204.60 ± 105.10			After	10	127.90 ± 13.57		
ST10	Before	10	131.10 ± 12.78	*0.029*	ST10	Before	10	130.60 ± 9.49	0.268	*0.012*
	After	10	185.30 ± 64.00			After	10	124.00 ± 12.95		
BFl7	Before	11	157.27 ± 45.35	0.260	BFl7	Before	11	147.27 ± 40.22	0.110	*0.048*
	After	11	152.00 ± 41.05			After	11	162.09 ± 43.58		
AM4	Before	10	137.10 ± 8.69	*0.047*	AM4	Before	9	142.11 ± 9.93	*0.042*	0.152
	After	10	145.10 ± 9.71			After	9	164.22 ± 23.54		
AM5	Before	11	136.27 ± 9.03	0.143	AM5	Before	11	134.82 ± 6.49	*0.002*	*0.010*
	After	11	144.09 ± 14.77			After	11	170.18 ± 24.73		
AM6	Before	11	140.45 ± 14.10	0.145	AM6	Before	11	137.36 ± 12.85	*0.002*	*0.003*
	After	11	146.73 ± 12.23			After	11	181.73 ± 31.38		
AM7	Before	11	145.18 ± 10.09	0.211	AM7	Before	11	148.00 ± 12.59	*0.003*	*0.001*
	After	11	140.27 ± 13.56			After	11	172.82 ± 16.09		

*LC = eccentric leg curl; L = lunge exercise; ST = semitendinosus; BFl = biceps femoris long head; AM = adductor magnus; RM = repeated measures significant differences between L and LC exercise; ANOVA = analysis of variance.

†The number after the muscle represents the section. Significant differences are marked in italics.

were evaluated for SI. The fMRI were transferred to a personal computer in the Digital Imaging and Communications in Medicine format and analyzed using image manipulation and analysis software (OSIRIX, University Hospital of Geneva, Switzerland). Individual baseline SI readings, analyzed using a standard region of interest (ROI), were established with the preliminary scan for each participant. The ROI was placed in the same position within the muscle for each measurement, avoiding blood vessels and bone, which potentially could have affected the analysis of the intensity changes. The SI was measured in a circular ROI (10–30 mm^2) within each muscle assessed before and after exercise, and percentage difference was calculated. The same technician (F.I.S.) performed the fMRI scan and the SI measures. Previous studies have shown high intertester reliability with intraclass correlation coefficients ranging from 0.87 to 0.94, respectively, for T2 measurements (8,9,13).

Statistical Analyses

The absolute STIR values were reported as mean ± *SD*. The exercise L or LC was set as the independent variable and the STIR of the muscles BFl, BFs, SM, ST, and AM for all the different sections (from 3 to 11) as the dependent variable. Given the differences between exercises used in this study, the principal comparison of interest was the within exercise pre-post changes in absolute values of STIR of the muscles (BFl, BFs, SM, ST, and AM) for all the different sections (3–7,10–13,15). To account for the main effects, a 2 factor (time × section), repeated measures analysis of variance with post hoc contrasts was used to determine significant differences between sections. Paired *t*-tests were used to determine significant pre-postexercise changes in L and LC and for the relative change between the LC and L exercises. The level of significance was set at $p < 0.05$. Statistical power of the study was >80% (from 80.2 to 84.7%). We supposed that mean change could be positive or negative.

Results

Typical STIR of the LC (right) and L (left) before and after exercise can be observed in Figure 1. No statistical differences ($p < 0.05$) were found in any muscle or section between left and right legs in the preexercise fMRIs. The

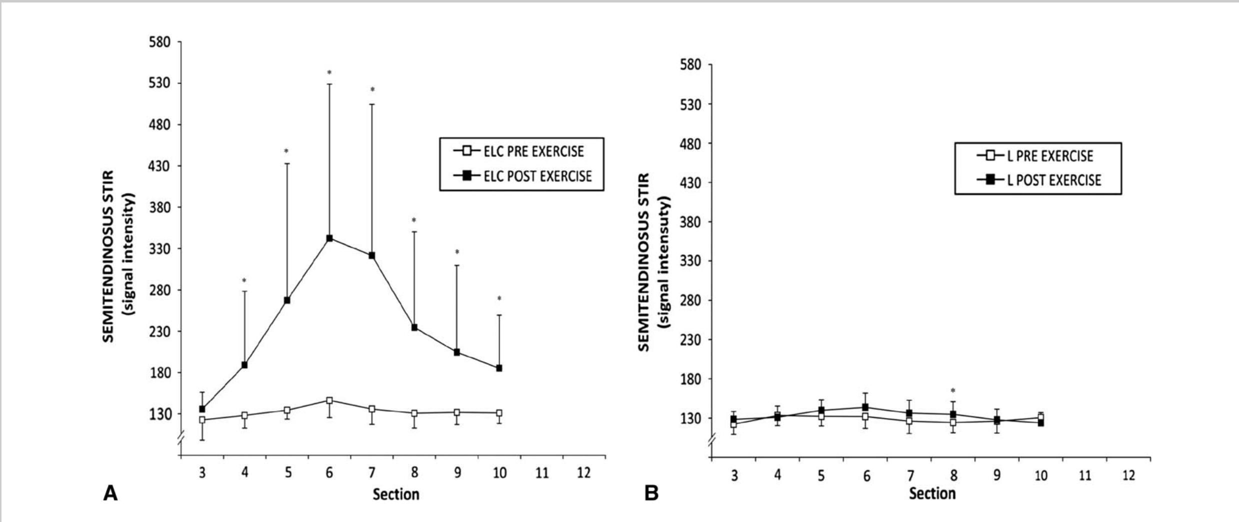

Figure 2. A, B) Semitendinosus absolute change (mean ± *SD*) from sections 3 to 12 pre (white color) and postexercise (black color) for LC (A) and L (B). * Denotes changes ($p < 0.05$) in preexercise and postexercise values.

changes in absolute values preexercise and postexercise of the different muscles (BFl, BFs, SM, ST, AM) and sections 3–12 for the LC and L exercises can be observed in Table 2. The following is a summary of the main findings from these tables.

For the ST muscle, significant changes (~21–45%, Table 2) in the STIR values for the LC exercise were noted along the length of the ST belly from sections 4 to 10 (Figure 2A); only section 8 was found to differ significantly ($p < 0.028$) from pretesting for the L exercise (Figure 2B). For the AM muscle, significant changes were observed for the L exercise proximally (sections 4–7, Figure 3A) (~2–13%), whereas a significant increase in STIR was only found for section 4 for the LC exercise (Figure 3B).

For the BFl, significant differences ($p = 0{,}048$, Figure 4A, B) were found postexercise for the LC and L exercise at

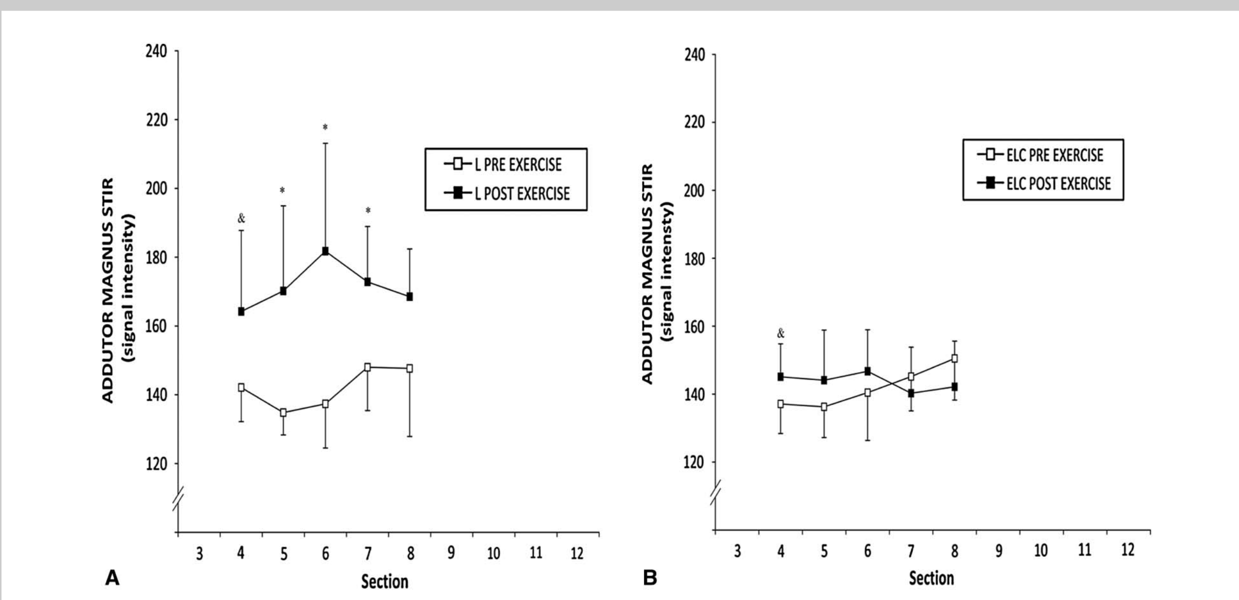

Figure 3. A, B) Adductor magnus absolute change (mean ± *SD*) from sections 3 to 12 pre (white color) and postexercise (black color) for L (A) and LC (B). * Denotes changes ($p < 0.05$) postexercise with analysis of variance and *t*-test. δ Denotes significant changes with *t*-test.

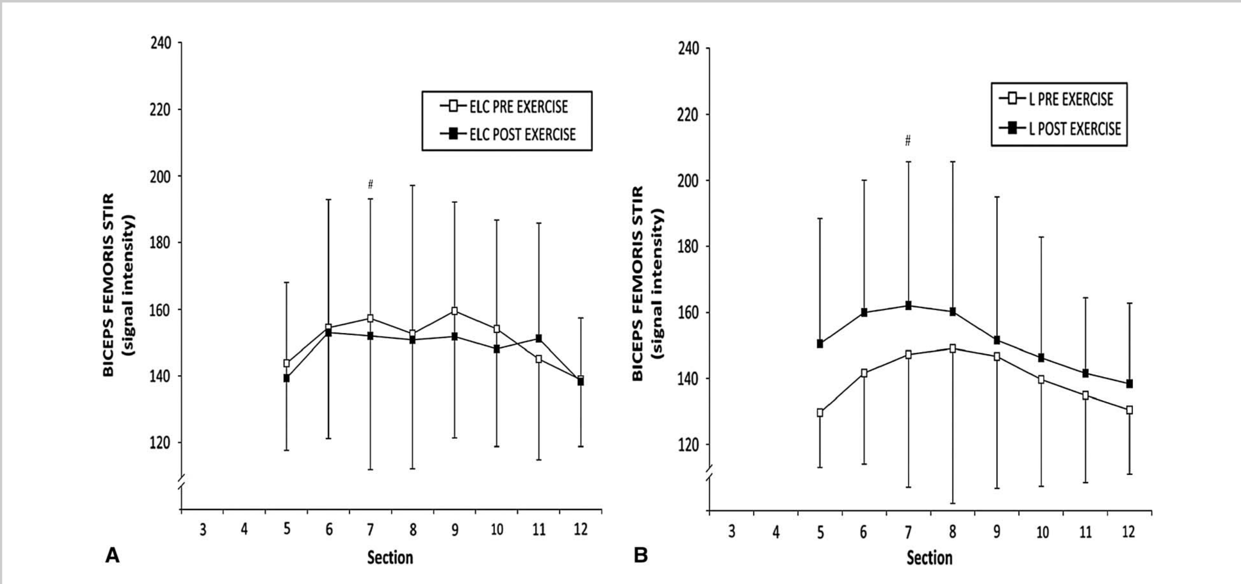

Figure 4. A, B) Biceps femoris long head absolute change (mean ± *SD*) from sections 3 to 12 preexercise (white color) and postexercise (black color) for LC exercise (A) and L exercise (B). # Denotes changes ($p < 0.05$) between prevalues and postvalues.

section 7 (~ −3 vs. 8%). No significant changes were observed in absolute STIR values for the SM and BFs muscles.

Discussion

This study measured whether 2 different hamstring muscle exercises produced different effects on the posterior muscles of the thigh, as quantified by the absolute changes in the STIR values of fMRI. When prescribing hamstring strengthening exercises, individual hamstring muscles have been assumed to be activated in a similar manner. However, this is not the case, and we observed that each individual hamstring muscle responded differently during the L and LC exercises.

The mechanics of the exercises used in this investigation are intrinsically different: (a) LC is an open-kinetic chain exercise with differences in hip flexion and tibial rotation (26,30) compared with L, which is a closed kinetic chain exercise (22,23,36); (b) LC is mainly a monoarticular movement, whereas L is biarticular; (c) as a result, the moments around the joints and the length-tension/torque angle relationship of individual muscles will differ; (d) there is no concentric component in LC, contrary to what happens in L; and (e) LC was supramaximally loaded at 120% 1RM, which is not the case for L. We are aware of all these differences, and we therefore, do not discuss the possible comparison between L and LC in the above respects. We shall instead focus on the site-specific activation of each exercise and how each exercise may be used for appropriate conditioning of some components of the posterior muscle group.

With regards to the ST muscle, it appears that the greatest changes in fMRI measurements followed the LC loading, in agreement with the findings of previous research (25,33). These changes may relate to the architectural characteristics of ST: It has the longest fascicle length and smallest physiological cross-sectional area of the hamstring muscles (46). Also, it is a fusiform muscle compared with the more pennate BFl and SM muscles. Muscles containing long fascicles produce forces over large length ranges and at high shortening speeds because they have a large number of simultaneously contracting, serially arranged sarcomeres (5). These morphological properties of the ST muscle may have been selectively used to accomplish the eccentric knee-flexion exercise more efficiently.

The region-specific activation within the proximal, middle, and distal regions of the same muscle found in this study were in contrast to the findings of Kubota et al. (25), where significant differences between proximal and distal regions were detected. This was explained by the fact that the ST is the only hamstring muscle that is anatomically partitioned as defined by its architecture and innervation (46). In addition, this division into partitions is made even more evident by the presence of 2 different tendons, with each portion of the muscle receiving innervation from one nerve, or from a primary branch of a nerve (46). The differences between our findings and those of Kubota et al. (25) could be attributed to methodological differences, because we divided the thigh into 15 regions, whereas they only divided the thigh into 3 regions. In this investigation, only 1 section (section 8) of the ST showed changes after the lunge exercise.

In the AM muscle, significant changes (section 4, ~12%; section 5, ~19%; section 6, ~22%; and section 7, ~14%) were observed for the L exercise proximally (sections 4–7), compared with section 4 (5%) for the LC exercise. The greater damage evident in the AM during lunges is likely because the AM is a dominant hip extensor and its moment arm has actually been shown to be superior to the hamstrings and GM at 90° of hip flexion which is reached in the L exercise (32,44). The lesser involvement of the AM during the LC may be because of a fixed-hip flexion angle position (15°) during the exercise.

No significant changes in fMRI were observed for the BFl after LC loading. In contrast, significant absolute changes in STIR values were observed at 1 region (section 7) for the BFl after L loading. Because T2 values are more sensitive to eccentric exercise (21,25,27,37,39,40,48) compared with concentric exercise (27), this study supports previous findings where a very short and rapid period of eccentric hamstring contraction during the forward lunge has been documented (22,36). Hamstring length depends on both knee and hip-joint angles, because the hamstrings are biarticular muscles. The angle of the hip exerts a greater impact on the length of the BF than the angle of the knee (18,43), given the longer moment arm at the hip, and this relationship increases with increasing knee angle. Hip flexion-extension exercise resulted in greater BFl activation as measured by MRI compared with a fixed-hip exercise (25,34). Given this information, and based on muscle mechanics and physiology, greater BFl damage during lunges may result from larger internal hip-extension moments when the hip is flexed. Both BFl and AM are able to conserve their hip-extension moment arm with hip flexion in contrast to GM, which decreases its moment arm (44).

We do not know which variables produce site-specific activation differences between the 2 exercises. However, greater proximal activation (section 5, 23%; section 6, 10%; section 7, 8%; and section 8, 7%) is present after the L exercise (Figures 3A, B), whereas minimal or negative changes are evident after the LC exercise (section 5, 11%; section 6, −3%; section 7, −3%; and section 8, −4%). Exercise intensity might account for the finding that only one region showed significant changes for the BFl. Exercise-induced changes in fMRI are dependent on exercise intensity, because previous studies have reported greater SI changes after maximal loads compared with lower loads (1,4,14,16,20,41). To disentangle this load effect, more research is needed investigating whether a loaded lunge produces greater changes across the proximal BFl in comparison with the bodyweight lunge.

Practical Applications

This study used fMRI to assess the changes to muscles in the posterior aspect of the thigh after 2 different exercises. The information derived from this investigation enables the clinician, strength and conditioning coach and physiotherapist a better understanding of site-specific activation of the hamstrings. When the goal of a therapeutic or a conditioning intervention is to specifically load all regions of the ST, the LC exercise is better suited, whereas the proximal regions of the BFl and AM are better loaded during the L exercise. These results may lead to a new exercise classification criteria based in the targeted posterior thigh muscle and its location that can help clinicians in designing strengthening, rehabilitation and prevention programs.

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