THE EFFECTS OF ECCENTRIC TRAINING ON HAMSTRING MUSCLE ARCHITECTURE: A SYSTEMATIC REVIEW

Murat Emirzeoğlu[1], Tüzün Fırat[2], and Özlem Ülger[2]

[1]*Karadeniz Technical University, Faculty of Health Sciences,*
Department of Physiotherapy and Rehabilitation, Trabzon, Turkey
[2]*Hacettepe University, Faculty of Physical Therapy and Rehabilitation, Ankara, Turkey*

Abstract:

The architectural features of the hamstring muscle group are important to prevent injury or to reduce the risk of re-injury. Besides, eccentric training is often used in the rehabilitation of hamstring injuries. The aim of this systematic review was to examine changes created by eccentric training in hamstring muscle architecture and to determine the minimal values of training duration and intensity to achieve required functional changes. The research was conducted on the PubMed, Scopus, Web of Science, COCHRANE, CINAHL, and Pedro databases. Full-text studies examining the effect of eccentric training on at least one parameter of the hamstring muscle architecture were included in the review. Studies on cadavers and animals, and studies involving different types of training combined with eccentric training were excluded. Twelve of the 7954 studies met the set criteria. According to the results, eccentric training undoubtedly increases fiber length. However, the pennation angle tends to decrease. On the other hand, muscle thickness and cross-sectional area tends to increase depending on the eccentric training. Although the frequency, number of sets and number of repetitions in sets were similar in the examined studies, muscle architecture changes were different. We think that eccentric training duration and the number of repetitions in total or per training session seem to have an impact on muscle architecture. In order to determine the minimal eccentric training program that can create these changes, quality research is needed to examine the duration, intensity and methods of eccentric training.

Key words: exercise, athletes, wounds and injuries, power

Introduction

The hamstring consists of the biceps femoris long head (BFlh), biceps femoris short head (BFsh), semitendinosus (ST) and semimembranosus (SM) muscles and is a muscle group that creates movement simultaneously in two joints—the knee and the hip (Ahmad, et al., 2013; Kellis, 2018). Injuries of these muscles are especially common in athletes (Ekstrand, Waldén, & Hägglund, 2016; Okoroha, et al., 2019). Researchers have identified two different mechanisms related to hamstring injuries. These are eccentric stress and loading the joint at the end of the range of motion. In the mid-swing phase of the gait cycle, the hamstring muscles contract eccentrically with knee extension and hip flexion before switching to weight bearing (Yu, et al., 2018). Meanwhile, the hamstring reaches its maximum length and biceps femoris reaches 110% of its length (Thelen, et al., 2005). This increased eccentric stress leads to a high risk of injury in the hamstring muscle group, particularly of the BFlh.

Clinicians focus on eccentric training to prevent or reduce the risk of re-injury of hamstring (Bourne, et al., 2018). Eccentric strength of the injured side is significantly lower compared to the uninjured side (Timmins, Shield, Williams, Lorenzen, & Opar, 2015). To regain strength, eccentric training is performed with the help of isokinetic dynamometer and many exercises such as Nordic hamstring exercise and Razor hamstring curl are applied (Pollard, Opar, Williams, Bourne, & Timmins, 2019). After these training programs, hamstring muscle strength increases and the incidence of injuries decreases (Al Attar, Soomro, Sinclair, Pappas, & Sanders, 2017; Lovell, et al., 2018; Opar, et al., 2015; Petersen, Thorborg, Nielsen, Budtz-Jørgensen, & Hölmich, 2011; van der Horst, Smits, Petersen, Goedhart, & Backx, 2015). For example, Nordic hamstring exercise programs, which researchers mostly prefer, reduce injuries by up to 51% (Yu, et al., 2008).

Examining the relationship between eccentric training and muscle architecture is very important

to understand hamstring injuries. The term 'muscle architecture' is used to describe the configuration of fibers, and this is an important functional and biomechanical determinant of force generation and speed of muscle tendon unit and contains information on the anatomic properties of the muscle, such as the fiber length (FL), pennation angle (PA), muscle thickness (MT) and cross-sectional area (CSA) (Lieber, 2010). Changes in these characteristics are associated with the risk of muscle injury (Timmins, et al., 2016a). When the BFlh muscle has a history of injury, it has been shown to have low FL and high PA compared to the uninjured side (Timmins, et al., 2015). Eccentric training, which is one of the important parameters of injury, causes changes to these muscle architecture parameters (Bourne, et al., 2017; Duhig, et al., 2019). Examining these changes contributes to the prevention of injuries and helps clinicians to develop strategies (Ribeiro-Alvares, Marques, Vaz, & Baroni, 2018).

There is no consensus in literature about duration, frequency, and the number of sets and repetitions of eccentric training. This is also valid for the minimum training criteria that may lead to changes in muscle architecture. The aim of this systematic review was to examine the changes created by eccentric training on muscle architecture and to determine the minimal values for duration and intensity of training which can provide functional changes.

Table 1. Search strategy keywords

Group 1		Group 2
architecture		hamstring
fiber length		biceps femoris
pennation angle	and	semitendinosus
cross sectional area		semimembranosus
		eccentric
		nordic

Methods

The experimental approach encompassed a 3-step method: 1) literature search, 2) study selection, and 3) assesment of methodological quality

In the process of this review, the rules for the Preferred Reporting Items for Systematic Reviews and Meta-Analyzes (PRISMA) were applied. A protocol was registered in the International Prospective Register of Systematic Reviews, PROSPERO (CRD42019133815).

Literature search

For this systematic review, the PubMed, Scopus, Web of Science, COCHRANE, CINAHL and Pedro databases (1967-2019) were searched. The latest search was completed on March 31, 2019. Two different keyword sets were identified for the search. Keywords in group 1 were combined with
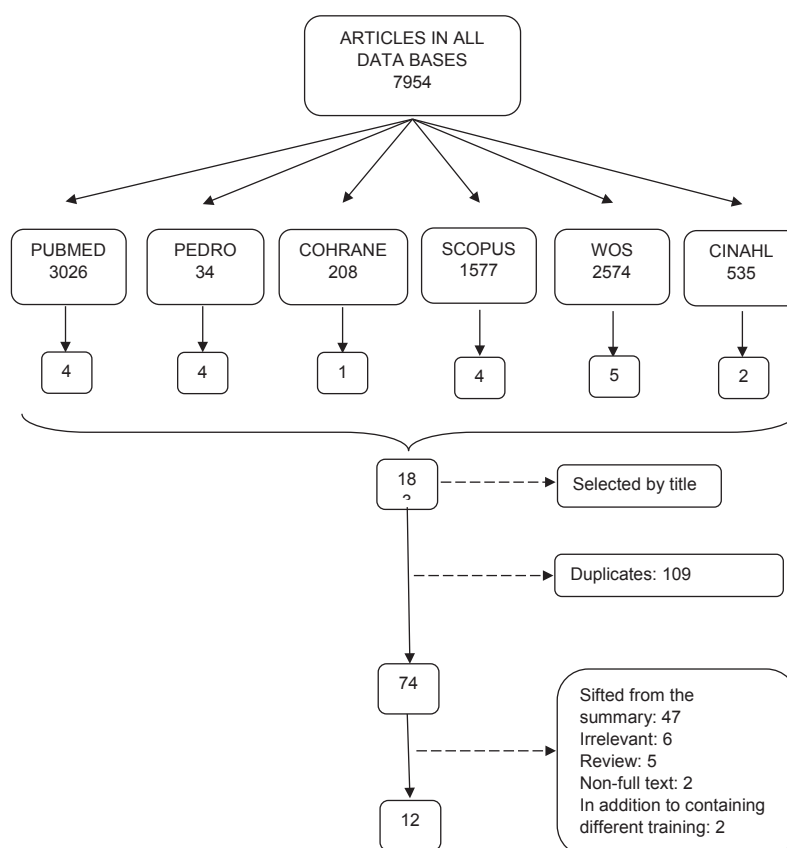

Figure 1. Diagram of the strategy used for study inclusion.

words in group 2 using conjunction "and". In this way, 24 different searches were performed in each database. The search strategy was determined by all researchers (Table 1).

Study selection

The studies, which included eccentric training for any of the muscles of the hamstring muscle group, examined at least one parameter of muscle architecture, written in English or Turkish, and published in full text were included in the review. Studies on cadavers and animals and involving additional training to eccentric training were excluded from the review. The researchers decided by consensus which articles should be included.

The titles of the studies were examined, and suitable articles were selected. Subsequently, articles from six databases were collated to eliminate duplicates. The remaining articles were reviewed according to the inclusion and exclusion criteria by looking at their abstracts and full texts if necessary. Full text articles that met the criteria were included in the review.

A total of 7954 articles were identified for this systematic review, mostly in the Pubmed database. According to the article title, 183 articles considered to be appropriate were included in the evaluation, of which 109 were then eliminated due to duplication. It was decided to exclude 47 of the remaining 74 articles after reviewing their abstracts. Six articles were excluded because they were not relevant, and six articles were eliminated due to the lack of full text. As a result, 12 articles that met the inclusion criteria were included in the review. The flow chart of the study selection is shown in Figure 1.

Assesment of methodological quality

The methodological quality of the articles in the review was evaluated using the PEDRO scale. The first item of the 11-item PEDRO scale, which examined whether the eligibility criteria were determined, was not used in the assessment because it did not affect internal or statistical validity and was related to the Delphi scale. The remaining 10 items were answered as yes or no, and the total score was calculated. In addition to the PEDRO scale, the methodological quality of the articles was also examined according to the classification described by Jovell and Navarro-Rubio (Jovell, & Navarro-Rubio, 1995). All included articles were evaluated by three researchers. When there was any difference in scoring, the researchers participated in a joint meeting and the final decision on the relevant item was made together.

According to the PEDRO scale, the scores of the studies ranged between 4 and 8 (Kubota, et al., 2007; Mendiguchia, et al., 2013; Severo-Silveira, et al., 2021). In the Jovell and Navarro-Rubio classifi-

cation (Jovell & Navarro-Rubio, 1995), the studies by Potier, Alexander, and Seynnes (2009), Riberio-Alvares et al. (2018), and Bourne et al. (2017) were found to be level III and the other studies were level VI (Table 2).

Results

Characteristics of the participants

There were 266 individuals in the scope of the studies included in this review. Two-hundred-three of these individuals were doing recreational physical activity. Of the other individuals, 34 were sedentary, 21 were rugby players and eight were football referees. The mean age of the individuals in the studies ranged from 20 to 30 years (Table 2).

Intervention

Nordic hamstring exercise was performed as eccentric training in eight studies (Alonso-Fernandez, Docampo-Blanco, & Martinez-Fernandez, 2018; Bourne, et al., 2017; Duhig, et al., 2019; Mendiguchia, et al., 2013; Pollard, et al., 2019; Presland, Timmins, Bourne, Williams, & Opar, 2018; Riberio-Alvares, et al., 2018; Severo-Silveira, et al., 2021). Among these studies, Nordic exercises were applied as constant and progressive by Severo-Silveira et al. (2021), as high and low intensity by Presland et al. (2018). Pollard et al. (2019) applied Nordic exercises with body weight (NHEbodyweighted) to one of the three groups, Nordic hamstring exercises with weight (NHEweighted) to the second group, and Razor hamstring curl with weight (RHCweighted) to the other group.

A hamstring curl machine was used in two of the four studies and isokinetic dynamometer was used in the others (Guex, Degache, Morisod, Sailly, & Millet, 2016; Kubota, et al., 2007; Potier, et al., 2009; Timmins, et al. 2016b). Guex et al. (2016) performed eccentric training in short and long positions of the muscle. Only Potier et al. (2009), Riberio Alvares et al. (2018), and Bourne et al. (2017) used a control group in their research.

In terms of training duration, Kubota et al. (2007) and Mendiguchia et al. (2013) applied a single session training. In the other 10 studies, training lasted a minimum of three and a maximum of 10 weeks (Bourne, et al., 2017; Guex, et al., 2016). The weekly frequency of the training sessions ranged from 1-3, the number of sets was 2-6, and the number of repetitions in sets ranged from 4-10. Potier et al. (2009) have implemented a detailed warm-up program. Presland et al. (2018), Pollard et al. (2019), Timmins et al. (2016b), Alonso-Fernandez et al. (2018), Mendiguchia et al. (2013), and Kubota et al. (2007) examined the long-term effects with measurements taken in the period following the training (Table 2).

Table 2. The subjects and characteristics of the studies included in this review

Studies/ Design	Subject (n), age (years)	Inclusion or exclusion criteria	Intervention	Duration (week) Frequency (d. wk-1) Sets Repetitions	Total number of repetitions / Total number of repetitions per training	Measurement time	Muscle Outcome measures	Main result	Jovell and Navarro-Rubio / Pedro Scores
Alanso-Fernandez et. al. (2018) *Cohort study*	23 male participants practicing recreational physical activity (25.2±3.3 yr)	included -with no history of lower limb injury in the past 12 months -no previous experience in eccentric training	NHE	8 / 2-3 / 2-3 / 4-10	462 / 21	at week 1, 9 and 13	BFlh / FL, PA, MT	FL↑ 23.9%, after the intervention vs baseline (p<.001) FL↓ 12.1%, after the 28-d detraining period vs after the intervention (p<.001) PA↓ 14.8%, after the intervention vs baseline (p<.001) PA↑ 9.2%, after the 28-d detraining period vs after the intervention (p<.001) MT↑ 7.7%, after the intervention vs baseline (p<.001) MT↓ 6.6%, after the 28-d detraining period vs after the intervention (p<.05)	VI / 5
Bourne et al. (2017) *Small-sample randomized controlled trials*	Total: 30 recreationally active participants -NHE: n=10, age 21.6±3.2 yr -Control group:n=10, age 21.3±3.7 yr	included -with no history soft tissue and orthopaedic injuries to the trunk, hips and lower limbs -had no known history of hamstring strain, anterior cruciate ligament or other traumatic knee injury.	NHE	10 / 2 / 2-6 / 5-10	686 (646-726) / 34.3 (32.3-36.3)	baseline, at week 5 and 10	BFlh, BFsh, ST, SM / FL, MT, CSA	FL↑ mid-training and after the intervention vs baseline in the eccentric group (p<.001) CSA and MT↑ after the intervention vs baseline in the eccentric group for all muscles. But, no significant difference between eccentric and control groups for BFlh and SM muscles	III / 6
Duhig et al. (2019) *Cohort study*	Total: 30 recreationally active males -Eccentric training group: n=15, 23.7±4.8 yr	included -with no history soft tissue and orthopaedic injuries to the lower limbs, hips, and trunk with no prior history of hamstring strain or knee ligament injury.	NHE	5 / 1-2 / 2-5 / 6	198 / 22	Baseline and at 5 week	BFlh / FL, PA, MT	FL↑ 13%, after the intervention vs baseline (p<.001) PA↓ 5%, after the intervention vs baseline (p=.001) MT↑ 7% after the intervention vs baseline (p<.001)	VI / 7
Guex et al. (2016) *Cohort study*	Total: 22 physical active subjects SML group: n=11, age: 27.3±3.9 yr -LML group:n=11, age: 28.4±4.5 yr	included -with no traumatological disorders, history of hip or knee pathology or dysfunction	Eccentric training on an isokinetic dynamometer	3 / 2-3 / 3-5 / 8	240 / 30	Baseline and at 3 week	BFlh / FL, PA	FL↑ 4.9% after the intervention vs baseline in the SML group (p<.01) FL↑ 9.3%, after the intervention vs baseline in the LML group (p<.001) PA↔ in both groups (p>.05)	VI / 6
Kubota et al. (2007) *Nonrandomized controlled prospective trials*	12 healthy young male (age 23.7±1.8 yr)	included -with no history of neuromuscular or orthopedic disease -none were participating in any regular training regime	Eccentric training with HCL	1 / 1 / 5 / 10	50 / 50	Baseline, immediately following exercise, and on the 1st, 2nd, 3rd and 7th days following the exercise	BFlh, BFsh, ST, SM / CSA	CSA ↔ BFlh and SM CSA↑ BFs distal region on the 2nd and 7th day after the intervention vs baseline (p<.003) CSA↑ ST proximal region on the 3rd day, middle region on the 2nd, 3rd, 7th and immediately after (p<.003) after the intervention vs baseline	VI / 4

Studies/Design	Subject (n), age (years)	Inclusion or exclusion criteria	Intervention	Duration (week) Frequency (d. wk-1) Sets Repetitions	Total number of repetitions / Total number of repetitions per training	Measurement time	Muscle Outcome measures	Main result	Jovell and Navarro-Rubio / Pedro Scores
Mendiguchia et al. (2013) *Nonrandomized controlled prospective trials*	8 male national-level soccer referees (age 29.50±4.72 yr)	included -with no injury to their legs or back in the past 12 months –if they were unsuitable for MRI	NHE	1 1 5 8	40 40	Baseline, after within 3 minutes and 72 hours	BF, ST, SM CSA	CSA↔ ST, SM, BFlh after with in 3 minutes and 72 hours vs baseline CSA↑ 36%,after with in 3 minutes vs baseline for nondominant BFsh (p=.025) CSA↑30% and 64% after 72 hours vs baseline for dominant and nondominant BFsh respectively (p=.035, p=.015)	VI 4
Pollard et al. (2019) *Cohort study*	30 recreationally active males -NHEbodyweight: n=10, age 24±4 yr) -NHEweighted: n=10, age 24±4 yr -RHCweighted: n=10, age 23±3 yr	included -with no injury to the lower limbs (including the hamstrings), wrist, or back in the past 18 months	NHE RHC	6 1-2 2-4 4-6	128 8	Weekly throughout the intervention and detraining periods (4 wk)	BFlh FL, PA, MT	Throughout the intervention FL↔ in the NHEbodyweight and RHCweighted groups (p>.05) FL↑ 9.94% 1stweek vs baseline in the NHEweighted group (p<.001) FL↑ 15.12% 2nd week vs baseline in the NHEweighted group (p<.001) FL↑ 15.63% 3rd week vs baseline in the NHEweighted group (p<.001) FL↑ 15.12% 4th week vs baseline in the NHEweighted group (p<.001) FL↑ 18.47% 5th week vs baseline in the NHEweighted group (p<.001) FL↑ 15.93% 6th week vs baseline in the NHEweighted group (p<.001) Detraining periods: FL↔ in the RHCweighted groups (p>.05) FL↓ 7.68% 2nd week vs post-intervention in the NHEbodyweight group (p<.05) FL↓ 8.35% 3rd weekvs post-intervention in the NHEbodyweight group (p<.05) FL↓ 8.93% 4th week vs post-intervention in the NHEbodyweight group (p<.001) FL↓ 8.40% 1st week vs post-intervention in the NHEweighted group (p<.001) FL↓ 12.6% 2nd week vs post-intervention in the NHEweighted group (p<.001) FL↓ 11.82% 3rd week vs post-intervention in the NHEweighted group (p<.001) FL↓ 15.4% 4th week vs post-intervention in the NHEweighted group (p<.001) PA↔ in the three groups (p>0.05) MT↔ in the three groups (p>0.05)	VI 7

Studies/ Design	Subject (n), age (years)	Inclusion or exclusion criteria	Intervention	Duration (week) Frequency (d. wk-1) Sets Repetitions	Total number of repetitions / Total number of repetitions per training	Measurement time	Muscle Outcome measures	Main result	Jovell and Navarro-Rubio / Pedro Scores
Potier et al. (2009) *Small-sample randomized controlled trials*	22 subjects -control group: n=11, age:29.6±1.2 yr -eccentric training group: n=11, age:27±0.8 yr	excluded -if they performed regular weight training to their lower limbs -they had any pre-existing musculoskeletal injuries or medical conditions limiting their ability to exercise	Eccentric training with HCM	8 3 3 8	576 72	Baseline and at 8 week	BFlh / FL, PA	FL↑ 33%, after the intervention vs baseline ($p<.01$) FL↔ the control group ($p=0.09$) but, ↑ 16.7% after the intervention vs baseline ($p<.001$) FL↔ when comparing the control group to the eccentric group ($p=.11$). PA↔ in either the control ($p=.22$) or the eccentric groups ($p=.38$) but, ↑ 6.47% in the control group and ↓ 2.92% in the eccentric group after the intervention vs baseline ($p<.001$)	III / 5
Presland et al. (2018) *Cohort study*	20 recreationally active males HI NHE: n=10, age 22.2±2.6 yr LI NHE: n=10, age 22.3±3.2 yr	included -with no history of lower limb, hamstring, back, hand, or wrist injury in the previous 36 months	NHE	HI: 6 2 4-5 6-10 LI 6 1-2 2-4 4-6	HI: 440 36.66 LI: 128 16	weekly during training and at 2 and 4 weeks of detraining	BFlh / FL, MT, PA	Unless otherwise stated, ratios and p values stated for HI and LI groups respectively FL↔ 1st week vs baseline, but ↑ 10.41% and 10% ($p>.05$) FL ↑ 16.2% week vs baseline, but 18.53% 2nd week vs baseline ($p<.05$) FL ↑ 20.43% and 19.22% 3rd week vs baseline ($p<.001$) FL ↑ 22.10% and 21.11 4th week vs baseline ($p<.001$) FL ↑ 22.10% and 20.41% 5th week vs baseline ($p<.001$) FL ↑ 23.37% and 23.88% 6th week vs baseline ($p<.001$) FL ↓17.35% and 15.2% after 2nd week vs post-intervention ($p<.001$) FL ↓19.90% and 17.84% after 4th week vs post-intervention $p<.001$) PA↔ 1st week vs baseline, but ↓ 7.12% and 9.17% ($p>.05$) PA↔ 2nd and 3rd week vs baseline, but ↓ 11.14 % and 14.32% ($p>.05$) in HI group PA ↓14.57% and 14.50% 2nd and 3rd week vs baseline ($p<.05$) in LI group PA ↓14.85% and 16.53 4th week vs baseline ($p<.001$) PA ↓14.70% and 16.39% 5th week vs baseline ($p<.001$) PA↔ 6th week vs baseline, but ↓ 13.57 ($p>.05$) in HI group PA ↓18.21 6th week vs baseline ($p<.001$) in LI group PA ↔after 2nd week vs post intervention but ↑ 14.85% and 16.53 ($p=.06$, $p=.09$) PA↑ 18.50% and 18.89% after 4th week vs post intervention ($p=.016$, $p=.003$) MT↔ both groups and all time	VI / 7

Studies/Design	Subject (n), age (years),	Inclusion or exclusion criteria	Intervention	Duration (week) Frequency (d. wk-1) Sets Repetitions	Total number of repetitions / Total number of repetitions per training	Measurement time	Muscle Outcome measures	Main result	Jovell and Navarro-Rubio / Pedro Scores
Riberio Alvares et al. (2018) *Small-sample randomized controlled trials*	20 physical active young adults -control group: n=10, age:26±2.7 yr -eccentric training group: n=10, age: 23.7±3.3 yr	excluded -history of lower limb injury with in the previous 12 months -history of previous hamstring strain throughout life; -musculoskeletal, respiratory, or cardiovascular conditions considered a risk or a limiting factor for maximal exercise; -users of nutritional supplements or anabolic steroids.	NHE	4 2 3 6-10	186 23.25	Baseline and at 4 week	BFlh *FL, PA, MT*	FL↑ 22% after the intervention vs baseline (p<.05) FL↔ in the control group (p>.05) PA↓ 17% after the intervention vs baseline (p<.05) PA↔ in the control group (p>.05) MT↔ after the intervention vs baseline (p<.05) MT ↔ in the control group (p>.05)	III 6
Severo-Silveira et al. (2021) *Cohort study*	21 rugby players -CTG: n=11, age 27.2±3.26 yr) -PTG: n=10, age 25.2±3.34 yr	excluded -history of muscle injury in the posterior thigh up to 6 months before the beginning of the study -current musculoskeletal injury or any illness that could impair the execution of NHE or isokinetic testing -noncompliance with the full NHE training program	NHE	CTG: 8 2 2-3 6 PTG: 8 2 2-4 6-10	CTG: 168 10.5 PTG: 456-488 28.5-30.5	Baseline and at 8 week	BFlh *FL, PA, MT*	FL↑ 7.44%, after the intervention vs baseline in the CTG (p<.001) FL↑ 10.15%, after the intervention vs baseline in the PTG (p<.001) MT↑ 6.61%, after the intervention vs baseline in the CTG (p=.001) MT↑ 7.56%, after the intervention vs baseline in the PTG (p<.001) PA↔ after the intervention vs baseline in the both group (p>.05)	VI 8

Outcome measurement

All articles included at least one parameter for muscle architecture. In this context, FL, PA and MT of BFlh were examined in seven studies (Alonso-Fernandez, et al., 2018; Duhig, et al., 2019; Pollard, et al., 2019; Presland, et al. 2018; Ribeiro-Alvares, et al. 2018; Severo-Silveira, et al., 2021; Timmins, et al., 2016b). In two of these studies B-mode ultrasonography system (Vividi; GE Medical Systems, Fairfield, CT; with a linear-array probe GE 8L; frequency: 13 MHz; depth: 6 cm; width: 4 cm, analysis through the Image J software; National Institutes of Health, USA) was used for imaging (Ribeiro-Alvares, et al. 2018; Severo-Silveira, et al., 2021). In both studies, measurements were taken from the midpoint of the distance between the ischial tuberositas and the upper limit of the fibular head.

In the other five studies, images were taken with an ultrasound with different characteristics (2D, B-mode ultrasound device; frequency: 12 MHz, depth: 8 cm, field of view: 14-47 mm; GE Healthcare Vividi, Wauwatosa) and evaluated with MicroDicom software V.0.7.8 Bulgaria (Alonso-Fernandez, et al., 2018; Duhig, et al., 2019; Pollard, et al., 2019; Presland, et al. 2018; Timmins, et al., 2016b). Using the same device and software as those researchers, Bourne et al. (2017) investigated the BFlh FL in their studies. In these six studies, measurements were taken from the midpoint of distance between the ischial tuberositas and the popliteal line.

In two of the studies FL and PA were evaluated (Guex, et al., 2016; Potier, et al., 2009). Potier et al. (2009) evaluated biceps femoris architecture with the Esaote Technos Plus device at 13 MHz, with ultrasound probe of 41 mm (LA424 14 8, Genova, Italy) without specifying whether it was short or long head. Guex et al. (2016) examined the BFlh muscle architecture with the SSD-2000 device (ALOKA, Tokyo, Japan) with the probe 42 mm linear array transducer, 10 MHz wave frequency. Mendiguchia et al. (2013) and Kubota et al. (2007) evaluated the CSA of all hamstring muscles in their studies using the 1.5-T whole-body imager with surface phased-array coils (Magnetom Avanto; Siemens, Erlangen, Germany, Magnetom Symphony; Siemens-Asahi Medical Technologies, Tokyo, Japan). Kubota et al. (2007) took measurements from the proximal, middle, and distal parts of the muscles. Bourne et al. (2018) evaluated the CSA of BFsh, ST and SM muscles using a 3-Tesla (Siemens TrioTim, Germany) imaging system with a spinal coil.

All researchers using ultrasound in their studies placed the subjects prone with the hip in a neutral position (Alonso-Fernandez, et al., 2018; Bourne, et al., 2018; Duhig, et al., 2019; Guex, et al.,2016; Pollard, et al., 2019; Potier, et al., 2009; Presland,

Studies/ Design	Subject (n), age (years),	Inclusion or exclusion criteria	Intervention	Duration (week) Frequency (d. wk-1) Sets Repetitions	Total number of repetitions / Total number of repetitions per training	Measurement time	Muscle Outcome measures	Main result	Jovell and Navarro-Rubio / Pedro Scores
Timmins et al. (2016) *Cohort study*	Total: 28 recreationally active male Eccentric training group (n=14, 21.2±2.7 years)	included -with no history of lower limb injury in the past 12 months	eccentric training on an isokinetic dynamometer	6 2-3 4-6 6-8	582 34.23	at 28 day prebaselin, baseline; and days 14, 21, and 42 of the intervention and then again after 28 d of detraining	BFlh / FL, PA, MT	0% MVIC FL↑ 14.83%, 14th day vs baseline (p<.001) FL↑ 15.09%, 21st day vs baseline (p<.001) FL↑ 16.39%, 42nd day vs baseline (p<.001) FL↓ 11.69%, after the 28-d detraining period vs after the intervention (p<.001) PA↓ 9.68%, 14th day vs baseline (p<.05) PA↓ 8.28%, 21st day vs baseline (p<.05) PA↓ 7.54%, 42st vs baseline (p<0.05) PA↔ but ↑ 8% after the 28-d detraining period vs 42nd day (p>05) MT↔ (p>.05)	VI 7

Note. ↑: increase, ↓: decrease, ↔: no significant change, BFlh: biceps femoris long head, BFsh: biceps femoris short head, CSA: cross-sectional area, CTG: constant training group, FL: fiber length, HCM: hamstring curl machine, HI: high intensity, LML: long muscle length, LI: low intensity, MRI: magnetic resonance imaging, MT: muscle thickness, NHE: nordic hamstring exercise, PA: pennation angle, PTG: progressive training group RHC: razor hamstring curl, SM: semimembranosus, SML: short muscle length, ST: semitendinosus, yr: years.

et al. 2018; Ribeiro-Alvares, et al. 2018; Severo-Silveira, et al., 2021; Timmins, et al., 2016b). Researchers using MRI in their measurements positioned the subjects supine (Kubota, et al., 2007; Mendiguchia, et al., 2013). Mendiguchia et al. (2013) and Bourne et al. (2017) obtained images with the knees extended, whereas Kubota et al. (2007) took measurements of the knees in flexion.

Fiber length

Researchers evaluating the same muscle architecture parameters with the same device found that BFlh FL increased after training. Duhig et al. (2019), Pollard et al. (2019), and Alonso-Fernandez et. al. (2018) reported that five, six and eight weeks of training increased BFlh FL (p <.001, d = 2.0; p <.001, d = 1.41; p <.001, d = 2.28, respectively).

Pollard et al. (2019) showed that the training providing a significant increase in FL between the groups was NHEweighted and that there was no significant change in the NHEbodyweighted and RHCweighted groups. Presland et al. (2018) showed that both high and low intensity eccentric training increased BFlh FL. In another study, Timmins et al. (2016b) examined FL in the second and third weeks of a 6-week training program and at the end of the training; FL showed a significant increase in the second, third and sixth weeks in the measurements of 0%, 25%, 50% and 75% of the maximum voluntary isometric contraction (p<.05, d = 2.65-2.98).

Riberio Alvares et al. (2018) and Severo-Silveira et al. (2021) used US with different frequency and depth characteristics and evaluated BFlh FL in their studies. An increase in FL was determined after four and eight weeks of training. Severo-Silveira et al. (2021) showed that there was an increase in both groups but this increase was higher in the progressive training group (PTG) than the constant training group (CTG) (p<.001, d=0.29; p<.001, d=0.35, respectively).

Potier et al. (2009) evaluated FL with different devices and found a significant increase after eight weeks of training. Guex et al. (2016) and Bourne et al. (2017) reported an increase in BFlh FL after the shortest and longest training programs of three and ten weeks, respectively. Similarly, Bourne et al. (2007) showed that FL increased in the fifth and tenth weeks of eccentric training (p <.001, d = 1.39; p <.001, d = 2.17, respectively). Guex et al. (2016) explained that the eccentric training applied in the long position of the muscle increased the FL more than the training in the short position.

Potier et al. (2009), Riberio Alvares et al. (2018), and Bourne et al. (2007) stated that there was no significant change in FL in the control groups.

During the post-training follow-up, Pollard et al. (2019) reported that FL was significantly reduced in the NHEweighted group at the first, second, third and fourth weeks after the training

compared to the measurements taken at the end of six weeks of training. This significant change was also observed in the NHEbodyweighted group at weeks 2, 3 and 4 after training. There was no significant change in the RHCweighted group. Similar to the findings reported by Pollard et al. (2019), Timmins et al. (2016b) and Alonso-Fernandez et al. (2018) reported that FL decreased four weeks after training compared to the measurements taken at its end (Table 2).

Pennation angle

With the exception of the study by Bourne et al. (2007), the PA was also evaluated in all nine studies examining FL (Alonso-Fernandez, et al., 2018; Duhig, et al., 2019; Guex, et al.,2016; Pollard, et al., 2019; Potier, et al., 2009; Presland, et al. 2018; Ribeiro-Alvares, et al. 2018; Severo-Silveira, et al., 2021; Timmins, et al., 2016b). Presland et al. (2018) reported a significant decrease in PA in both low- and high-intensity groups during the six-week training period. This significant decrease started to occur in the second and fourth weeks of the program in the groups receiving low intensity (LI) and high intensity (HI) training, respectively. The HI training group showed no significant change after six weeks of training compared to baseline.

The decrease in the PA after four, five and eight weeks of eccentric training was reported by Riberio Alvares et al. (2018), Duhig et al. (2019) (p=.001, d=0.52), and Alonso-Fernandez et al. (2018) (p<.001, d=2.3), respectively. Timmins et al. (2016b) found that the PA decreased significantly at 0% maximum voluntary contraction in the second week of training, but this decrease occurred in the sixth week of training for all contraction intensities. The highest decrease in 0% maximum voluntary contraction measurements taken during the training period was in the second, third and sixth week, respectively.

Polard et al. (2019) stated that the PA decreased in the NHEweighted group during training, but this was not significant. There was no change in the NHEbodyweighted and RHCweighted groups during this six-week period.

Severo Silveira et al. (2018) reported that the PA did not change significantly in either the CTG or PTG group after eight weeks of training. In a similar study, Potier et al. (2009) reported no significant change in PA after eight weeks of training. Guex et al. (2016) reported that although the PA tended to decrease in the LML group, there was no significant change in either the LML or SML group.

Presland et al. (2018) reported an increase in PA in both HI and LI groups two weeks after the training compared to post-training, but this did not change significantly (HI: p=.060, d=1.75; LI: p=.098, d=1.33). The researchers stated that there was a significant increase in the measure-

ments taken in both groups (HI: p=.016, d=1.83; LI: p=.003, d=1.99) four weeks after the end of training. Similarly, Alonso-Fernández et al. (2018) found that the PA showed a significant increase (p<.001, d=1.36) compared to post-training in measurements taken four weeks after training. Polard et al. (2019) stated that the increase in the PA was higher in the NHEweighted group compared to the NHEbodyweighted group at two weeks post-training, and that these increases were not significant. In the RHCweighted group, there was no change in follow-up after training. In the study conducted by Timmins et al. (2016b), although there was an increase in PA, there was no significant difference between the measurements taken four weeks after training and the measurements taken at its end (Table 2).

Muscle thickness

Of all the studies in this review, MT was examined in eight studies, four of which showed no significant change in MT (Pollard, et al., 2019; Presland, et al. 2018; Ribeiro-Alvares, et al. 2018; Timmins, et al., 2016b). In three of the other studies, BFlh MT increased by approximately 8% (Alonso-Fernández, et al., 2018; Duhig, et al., 2019; Severo-Silveira, et al., 2021). Severo Silveira et al. (2021) showed an increase after training in both CTG and PTG groups (CTG: p=.001, d=0.60; PTG: =p<.001, d=0.54). Bourne et al. (2017) stated that training increased the thickness of ST and SM muscles and this increase was the highest in ST. It was also reported that the increase in BFsh muscle thickness was higher than in BFlh.

Alonso-Fernández et al. (2018) reported that MT decreased significantly four weeks after training compared to post-training (Table 2).

Cross sectional area

Only three of the studies in this review examined CSA. Mendiguchia et al. (2013) reported that the CSA of BFlh, ST and SM muscles did not change when measured within three minutes and 72 hours after training. BFsh muscle increased on the non-dominant side in the third minute and increased on both sides after 72 hours. No difference between the dominant and non-dominant sides in all measurements at all times was observed. Similarly, Kubota et al. (2007) found no significant change in BFlh and SM muscles immediately after training, or at days 1, 2, 3, or 7. However, in this study, the CSA was found to be increased in the proximal part of the ST muscle on the third day and in the middle part immediately after training and at days 2, 3 and 7. There was a significant increase in the distal part of BFsh muscle at days 2 and 7 following the training. In the study conducted by Bourne et al. (2017), which had the longest training period, the CSA of the four muscles in the hamstring group

increased after ten weeks of eccentric training. However, similar to the findings of Kubota et al. (2007) and Mendiguchia et al. (2013), the increase in BFlh and SM muscles was not statistically significantly higher compared to that of the control group (Table 2).

Discussion and conclusions

In this systematic review, the effect of eccentric training on the muscle architecture of the hamstring muscles was investigated. Twelve articles in total, the oldest from 2007 and the most recent from 2019, were included in this review. MR was used in two of these articles and the CSA was examined (Kubota, et al., 2007; Mendiguchia, et al., 2013). In nine studies, FL and/or PA and/or MT and/or CSA were examined using ultrasound (Alonso-Fernández, et al., 2018; Duhig, et al., 2019; Guex, et al., 2016; Pollard, et al., 2019; Potier, et al., 2009; Presland, et al. 2018; Ribeiro-Alvares, et al., 2018; Severo-Silveira, et al., 2021; Timmins, et al., 2016b). Bourne et al. (2017) examined muscle architecture parameters using both MR and ultrasound. The eccentric training programs in all the studies were evaluated in terms of muscle architecture considering similarities and differences.

Fiber length

Fiber length is the most commonly examined muscle architecture parameter in this review. Regardless of duration, frequency, number of sets and number of repetitions in a training session or in total, eccentric training increases FL of the biceps femoris muscle. FL was increased with both two-week training and ten-week training (Bourne, et al., 2017; Timmins, et al., 2016b). Bourne et al. (2017) did not specify a percentage increase in FL in their study. However, the highest increase in FL, of about 34%, was reported by Potier et al. (2009) with eight weeks of training. This was the first study to show the increase in FL in biceps femoris muscle with eccentric training and is the study with the highest number of repetitions per training session in this review. When examined in terms of the total number of repetitions in the training, Timmins et al. (2016b) implemented a similar intensity and Bourne et al. (2017) conducted a more intensive training compared to Potier et al. (2009). However, the number of repetitions per training session is smaller in these studies. The percentage increase in FL in the Timmins et al.'s (2016b) study is also smallers than that of Potier et al.'s (2009), although it can not be calculated from the Bourne et al.'s (2017) study. Timmins et al. (2016b) reported no clinically significant difference between the measurements taken at the second, third and sixth weeks of training. According to these findings, the increase in FL can be considered to be dependent on the number of

repetitions per training session, not the duration of the training program.

Severo Silveira et al. (2018) showed that progressive training leads to a greater increase in FL. However, in the study conducted by Presland et al. (2018), both the HI and LI training were seen to provide a similar increase in FL. Guex et al. (2016) reported that even if the training intensity was the same, when the muscle was trained in the long position, FL increased approximately two-fold compared to training in the short position. It can also be seen in the study conducted by Pollard et al. (2019)—the application method of eccentric training affects FL. Similarly, in a study conducted for the vastus lateralis muscle outside the scope of the study, it was stated that eccentric training provided a greater increase in FL when applied at a faster speed (Stasinaki, Zaras, Methenitis, Bogdanis, & Terzis, 2019).

In the light of this information, it can be said that eccentric training will undoubtedly increase FL, and this increase may vary depending on muscle position, intensity of training, training progression and training method. When the measurements taken during the follow-up period from one week to four weeks after training are examined, the significant decrease in FL shows that the gains obtained will be lost in a short time.

Pennation angle

With the exception of Bourne et al. (2017), all the researchers investigating FL evaluated the PA. Contrary to the increase in FL, there was a decrease or no significant change in PA with eccentric training.

In the study conducted by Timmins et al. (2016b), although the PA showed a significant decrease in the two-week period of training, it did not continue to decrease in the following four-week period. Alonso-Fernandez et al. (2018) showed that the PA decreased more substantially after eight weeks of training compared to this study. Ribeiro et al. (2018) reported the largest percentage change, although they applied the shortest duration training. The stage of training at which the decrease was more intensive was not stated by Alonso-Fernandez et al. (2018) or Riberio et al. (2018). In the light of the findings in these studies, it can be considered that the PA may not be related to the duration of training, or the number of repetitions per training session or in total. The short or long position of the muscle and the progressive training did not change the PA (Guex, et al., 2016; Severo-Silveira, et al., 2021). However, lower intensity rather than high intensity training was seen to lead to a decrease in the PA (Presland, et al., 2018).

When the PA is examined after training, it can be seen that the decrease obtained in training tended to progress after training. This significant increase

of decrease occurs at the earliest at week four after training. This decrease in PA observed in the post-training period may be related to the number of repetitions per training, although not to the duration of the training nor the total number of repetitions. A greater number of repetitions per training session may contribute to a longer maintenance of the reduced PA after training.

Muscle thickness

When the studies included in this review were examined, eccentric training was seen to provide an increase in hamstring MT or did not make any significant change. The increase in MT disappears considerably within four weeks after training (Alonso-Fernandez, et al., 2018). In studies showing an increase in BFlh MT, the duration of training varied between 5-10 weeks. With a training program of only 5 weeks, Duhig et al. (2019) reported a similar increase to that obtained by Alonso-Fernandez et al. (2018) and Severo Silveira et al. (2018). Similarly, although it was performed on different muscles, the thickness of the rectus femoris and vastus lateralis muscles increased significantly after four weeks of eccentric training (6.96% and 5.01%, respectively). However, it was stated that the measurements taken in the 8th and 12th weeks of training did not show a significant difference from the measurements taken in the fourth week (van Dyk, Behan, & Whiteley, 2019). Therefore, the significant increase in MT can be considered not to be primarily related to duration. It was also shown that if the average number of repetitions in each training session is increased, there may be an increase in MT (Alonso-Fernandez, et al., 2018; Bourne, et al., 2017; Duhig, et al., 2019; Severo-Silveira, et al., 2021).

Cross sectional area

In the studies included in this review, the least examined muscle architecture parameter was CSA. Even if eccentric training is performed in a single session, there is a significant increase in the CSA, especially in the BFsh and ST muscles (Kubota, et al., 2007; Mendiguchia, et al., 2013). However, it is difficult to know the minimum duration of training, the number of repetitions per training session and the total number of repetitions that will change the muscle architecture, or to predict how long the gains will continue. This is more complex for BFlh and SM muscles, which did not show significant changes in the studies reviewed.

In this review, it was seen that there are many studies examining the architectural changes in the hamstring muscle group caused by eccentric training. From the architectural point of view, although the muscles in the medial (SM, ST) and lateral (BFlh, BFsh) sections show anatomic similarities to each other, there are architectural differ-

ences between the groups. This demonstrates that modeling hamstring muscles as a single muscle is not very accurate (Kellis, Galanis, Natsis, & Kapetanos, 2010; Kellis, Galanis, Kapetanos, & Natsis, 2012). Although the frequency, number of sets or number of repetitions in sets were similar in the some examined studies, muscle architecture changes were different. According to the results of studies, we think that the duration, intensity and method of trainings are important for hamstring muscle architectural parameters. In the light of these few high-quality studies, it can be said that eccentric training leads to an increase in FL and a decrease in PA for the hamstring muscle group. Nevertheless, this effect, expressed for the hamstring muscle group, cannot be generalized to other muscle groups.

Unlike the concentric loading model, the potential for excursion increases after eccentric training.

This, together with the ability of the muscles to transform, may give an idea for preparing muscles for other tasks in the case of excursion, for example, muscle or tendon transfers. Before a muscle with low excursion ability is transferred to a muscle with high excursion ability, FL can be increased by eccentric training. Of course, these views should be proven by further high-quality studies. While developing the training program, not only the gains achieved through training, but also the long-term effects covering the period following the training should be considered.

Another conclusion of this review is that architectural parameters should be evaluated together with functional parameters. With the proven effect on functional change of the architectural parameters, it can be deduced not only for the muscles in this review but also for other muscles of a similar architecture.

References

Ahmad, C.S., Redler, L.H., Ciccotti, M.G., Maffulli, N., Longo, U.G., & Bradley, J. (2013). Evaluation and management of hamstring injuries. *American Journal of Sports Medicine*, *41*(12), 2933-2947. doi: 10.1177/0363546513487063

Al Attar, W.S.A., Soomro, N., Sinclair, P.J., Pappas, E., & Sanders, R.H. (2017). Effect of injury prevention programs that include the Nordic hamstring exercise on hamstring injury rates in soccer players: A systematic review and meta-analysis. *Sports Medicine, 47*(5), 907-916. doi: 10.1007/s40279-016-0638-2

Alonso-Fernandez, D., Docampo-Blanco, P., & Martinez-Fernandez, J. (2018). Changes in muscle architecture of biceps femoris induced by eccentric strength training with Nordic hamstring exercise. *Scandinavian Journal of Medicine and Science in Sports, 28*(1), 88-94. doi: 10.1111/sms.12877

Bourne, M.N., Duhig, S.J., Timmins, R.G., Williams, M.D., Opar, D.A., Al Najjar, A., et al. (2017). Impact of the Nordic hamstring and hip extension exercises on hamstring architecture and morphology: Implications for injury prevention. *British Journal of Sports Medicine*, *51*(5), 469-477. doi: 10.1136/bjsports-2016-096130

Bourne, M.N., Timmins, R.G., Opar, D.A., Pizzari, T., Ruddy, J.D., Sims, C., et al. (2018). An evidence-based framework for strengthening exercises to prevent hamstring injury. *Sports Medicine*, *48*(2), 251-267. doi: 10.1007/s40279-017-0796-x

Duhig, S.J., Bourne, M.N., Buhmann, R.L., Williams, M.D., Minett, G.M., Roberts, L.A., et al. (2019). Effect of concentric and eccentric hamstring training on sprint recovery, strength and muscle architecture in inexperienced athletes. *Journal of Science and Medicine in Sport*, *22*(7), 769-774. doi: 10.1016/j.jsams.2019.01.010

Ekstrand, J., Waldén, M., & Hägglund, M. (2016). Hamstring injuries have increased by 4% annually in men's professional football, since 2001: A 13-year longitudinal analysis of the UEFA Elite Club injury study. *British Journal of Sports Medicine*, *50*(12), 731-737. doi: 10.1136/bjsports-2015-095359

Guex, K., Degache, F., Morisod, C., Sailly, M., & Millet, G.B. (2016). Hamstring architectural and functional adaptations following long vs. short muscle length eccentric training. *Frontiers in Physiology, 7*, 1-9. doi: 10.3389/fphys.2016.00340

Jovell, A.J., & Navarro-Rubio, M.D. (1995). Evaluation of scientific evidence. *Medicine Clinica,* 105, 740-743.

Kellis, E. (2018). Intra- and inter-muscular variations in hamstring architecture and mechanics and their implications for injury: A narrative review. *Sports Medicine*, *48*(10), 2271-2283. doi: 10.1007/s40279-018-0975-4

Kellis, E., Galanis, N., Kapetanos, G., & Natsis, K. (2012). Architectural differences between the hamstring muscles. *Journal of Electromyography and Kinesiology*, *22*(4), 520-526. doi: 10.1016/j.jelekin.2012.03.012

Kellis, E., Galanis, N., Natsis, K., & Kapetanos, G. (2010). Muscle architecture variations along the human semitendinosus and biceps femoris (long head) length. *Journal of Electromyography and Kinesiology*, *20*(6), 1237-1243. doi: 10.1016/j.jelekin.2010.07.012

Kubota, J., Ono, T., Araki, M., Torii, S., Okuwaki, T., & Fukubayashi, T. (2007). Non-uniform changes in magnetic resonance measurements of the semitendinosus muscle following intensive eccentric exercise. *European Journal of Applied Physiology*, *101*(6), 713-720. doi: 10.1007/s00421-007-0549-x

Lieber, R. (2010). *Skeletal muscle, structure, functionand plasticity: The physiological basis of rehabilitation* (3rd ed.). Philadelphia: Lippincott Williams and Wilkins.

Lovell, R., Knox, M., Weston, M., Siegler, J.C., Brennan, S., & Marshall, P.W.M. (2018). Hamstring injury prevention in soccer: Before or after training? *Scandinavian Journal of Medicine and Science in Sports*, *28*(2), 658-666. doi: 10.1111/sms.12925

Mendiguchia, J., Arcos, A.L., Garrues, M.A., Myer, G.D., Yanci, J., & Idoate, F. (2013). The use of MRI to evaluate posterior thigh muscle activity and damage during Nordic hamstring exercise. *Journal of Strength and Conditioning Research*, *27*(12), 3426-3435. doi: 10.1519/JSC.0b013e31828fd3e7

Okoroha, K.R., Conte, S., Makhni, E.C., Lizzio, V.A., Camp, C.L., Li, B., et al. (2019). Hamstring injury trends in major and minor league baseball: Epidemiological findings from the major league baseball health and injury tracking system. *Orthopaedic Journal of Sports Medicine*, *7*(7), 1-7. doi: 10.1177/2325967119861064

Opar, D.A., Williams, M.D., Timmins, R.G., Hickey, J., Duhig, S.J., & Shield, A.J. (2015). Eccentric hamstring strength and hamstring injury risk in Australian footballers. *Medicine and Science in Sports and Exercise*, *47*(4), 857-865. doi: 10.1249/MSS.0000000000000465.

Petersen, J., Thorborg, K., Nielsen, M.B., Budtz-Jørgensen, E., & Hölmich, P. (2011). Preventive effect of eccentric training on acute hamstring injuries in men's soccer: A cluster-randomized controlled trial. *American Journal of Sports Medicine*, *39*(11), 2296-2303. doi: 10.1177/0363546511419277

Pollard, C.W., Opar, D.A., Williams, M.D., Bourne, M.N., & Timmins, R.G. (2019). Razor hamstring curl and Nordic hamstring exercise architectural adaptations: Impact of exercise selection and intensity. *Scandinavian Journal of Medicine and Science in Sports*, *29*(5), 706-715. doi: 10.1111/sms.13381

Potier, T.G., Alexander, C.M., & Seynnes, O.R. (2009). Effects of eccentric strength training on biceps femoris muscle architecture and knee joint range of movement. *European Journal of Applied Physiology*, *105*(6), 939-944. doi: 10.1007/s00421-008-0980-7

Presland, J.D., Timmins, R.G., Bourne, M.N., Williams, M.D., & Opar, D.A. (2018). The effect of Nordic hamstring exercise training volume on biceps femoris long head architectural adaptation. *Scandinavian Journal of Medicine and Science in Sports*, *28*(7), 1775-1783. doi: 10.1111/sms.13085

Ribeiro-Alvares, J.B., Marques, V.B., Vaz, M.A., & Baroni, B.M. (2018). Four weeks of Nordic hamstring exercise reduce muscle injury risk factors in young adults. *Journal of Strength and Conditioning Research*, *32*(5), 1254-1262. doi: 10.1519/JSC.0000000000001975

Severo-Silveira, L., Dornelles, M.P., Lima-E-Silva, F.X., Marchiori, C.L., Medeiros, T.M., & Pappas, E., et al. (2021). Progressive workload periodization maximizes effects of Nordic hamstring exercise on muscle injury risk factors. *Journal of Strength and Conditioning Research, 35*(4), 1006-1013. doi: 10.1519/JSC.0000000000002849

Stasinaki, A.N., Zaras, N., Methenitis, S., Bogdanis, G., & Terzis, G. (2019). Rate of force development and muscle architecture after fast and slow velocity eccentric training. *Sports (Basel)*, *7*(2), 1-12. doi: 10.3390/sports7020041

Thelen, D.G., Chumanov, E.S., Hoerth, D.M., Best, T.M., Swanson, S.C., Li, L., et al. (2005). Hamstring muscle kinematics during treadmill sprinting. *Medicine and Science in Sports and Exercise, 37*(1), 108-114. DOI:10.1249/01.mss.0000150078.79120.c8

Timmins, R.G., Bourne, M.N., Shield, A.J. Williams, M.D., Lorenzen, C., & Opar, D.A.(2016a). Short biceps femoris fascicles and eccentric knee flexor weakness increase the risk of hamstring injury in elite football (soccer): A prospective cohort study. *British Journal of Sports Medicine*, *50*(24), 1524-1535. doi: 10.1136/bjsports-2015-095362

Timmins, R.G., Ruddy, J.D., Presland, J., Maniar, N., Shield, A.J., Williams, M.D., et al. (2016b). Architectural changes of the biceps femoris long head after concentric or eccentric training. *Medicine and Science in Sports and Exercise, 48*(3), 499-508. doi: 10.1249/MSS.0000000000000795

Timmins, R.G., Shield, A.J., Williams, M.D., Lorenzen, C., & Opar, D.A. (2015). Biceps femoris long head architecture: A reliability and retrospective injury study. *Medicine and Science in Sports and Exercise, 47*(5), 905-913. doi: 10.1249/MSS.0000000000000507

van der Horst, N., Smits, D.W., Petersen, J., Goedhart, E.A., & Backx, F.J. (2015). The preventive effect of the Nordic hamstring exercise on hamstring injuries in amateur soccer players: A randomized controlled trial. *American Journal of Sports Medicine*, *43*(6), 1316-1323. doi: 10.1177/0363546515574057

van Dyk, N., Behan, F.P., & Whiteley, R. (2019). Including the Nordic hamstring exercise in injury prevention programmes halves the rate of hamstring injuries: A systematic review and meta-analysis of 8459 athletes. *British Journal of Sports Medicine, 53*(21), 1362-1370. doi: 10.1136/bjsports-2018-100045

Yu, B., Queen, R.M., Abbey, A.N., Liu, Y., Moorman, C.T., & Garrett, W.E. (2008). Hamstring muscle kinematics and activation during over ground sprinting. *Journal of Biomechanics, 4*l(15), 3121-3126.

Correspondence to:
Murat Emirzeoğlu
Karadeniz Technical University, Faculty of Health Sciences
Department of Physiotherapyand Rehabilitation
61080 Trabzon, Turkey
Phone: +90 462 377 8863
Fax: +90 462 230 0475
E-mail: muratemirzeoglu@gmail.com