Influence of Resistance Training Variables and the Nordic Hamstring Exercise on Biceps Femoris Architectural Adaptations in Soccer Players: A Systematic Review

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Context: Manipulation of resistance training variables influences the structural and functional adaptations of muscle, having a great impact on sport performance and hamstring injury prevention.

Objective: To analyze how the main resistance training variables affect the biceps femoris long head architecture in soccer players.

Data Sources: Five databases were searched from inception to January 2024.

Study Selection: Studies that included training intervention groups and measured muscle architecture adaptations before and after the training program in soccer players were included.

Study Design: Systematic review with meta-analysis.

Level of Evidence: Level 2.

Data Extraction: Muscle thickness, fascicle length, and pennation angle were extracted from included studies as main outcomes.

Results: Six studies and 12 training groups (168 participants) were analyzed. The effects of Nordic hamstring exercise (NHE) against soccer interventions, volume of training, and frequency of training as independent variables were analyzed. NHE significantly improved biceps femoris long head fascicle length ($P = 0.01$). Training twice a week did not show significant differences compared with training once a week. Higher volumes of training (ie, >290 repetitions) in a period of 6 to 12 weeks with 57 repetitions per week demonstrated significant effects.

Conclusion: NHE lengthens the fascicle, especially if a sufficient volume (ie, >290 repetitions) and 2 days per week are performed. It is still unknown how the programming of some fundamental variables such as intensity, degree of effort, or exercise selection affects the muscle architecture of the biceps femoris long head.

Keywords: fascicle length; muscle architecture; muscle thickness; pennation angle; strength

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Resistance training has been shown to substantially reduce injury risk as well as enhance sport performance.[26,51] One of the most important determining factors for strength production is muscle architecture, which is considered a good predictor of muscle function.[28] Muscle architecture can be defined as the geometric characteristics of the fiber and/or tendon.[14] It can be also defined as the number and orientation of the muscle fibers within a muscle.[28] Muscle architecture has 3 main components: muscle thickness, fascicle length, and pennation angle,[28] and is usually observed by ultrasonography or magnetic resonance imaging (MRI).[12] Muscle architecture can be modified through resistance training.[49] However, it is important to note that adaptations derived from resistance training depend directly on the programming of variables, especially intensity, volume, exercise selection, degree of effort (ie, the number of repetitions actually performed in each set with respect to the maximum number that can be completed), or frequency.[44]

Furthermore, muscle architecture, and especially fascicle length, has been shown to be associated with injury risk in professional soccer players (ie, shorter fascicles are associated with higher injury risk).[52] Hamstring injuries constitute a severe problem to the clubs, since injury rates have increased during recent seasons, constituting 24% of all injuries in soccer.[10] In addition, the impact of injuries on team performance in soccer is well known.[20] Therefore, efforts should be made to reduce the high injury incidence in this muscle group in soccer players. Consequently, several studies have studied the effects of resistance training programs to lengthen muscle fascicles and thus reduce hamstring injury risk.[16,29,34] In this context, the Nordic hamstring exercise (NHE) is a very common strategy to enhance both eccentric strength levels as well as to increase the length of the fascicle in soccer players.[34,54]

Therefore, understanding how modifying resistance training variables affect derived adaptations can help optimize the training process and prevent hamstring injuries—the most common muscle injury in soccer players, especially the biceps femoris long head.[19] These injuries are usually observed during high-speed running, with hip flexion and extended knee, thus increasing muscle strain.[8] In this context, muscle architecture plays an important role in muscle excursion, and this could compromise the hamstrings in these elongated positions.[28,53] Thus, the aim of the present systematic review was to analyze how some of the most important resistance training variables (ie, intensity, frequency, exercise selection, and degree of effort) affect derived adaptations on muscle architecture (ie, muscle thickness, fascicle length, and pennation angle). The specific objectives were to: (1) analyze the effects of different types of loads (ie, heavy loads of ≥85% repetition maximum (RM) vs lower loads of <85% RM) on biceps femoris long head architecture; (2) study how different exercises (ie, hip-dominant vs knee-dominant hamstring exercises) affect biceps femoris long head architecture; (3) study the effectiveness of NHE in improving the biceps femoris long head architecture due to the large interest in the use of the NHE in resistance training programs to reduce injury risk and to increase eccentric strength of the hamstrings[2,4,33]; (4) explore adaptations in the long head architecture of the biceps femoris depending on the frequency of training (ie, 1 vs 2 or more days of training); (5) analyze the effects of different degrees of effort (ie, until muscle failure vs submaximal efforts) on the long head architecture; and (6) assess whether higher volumes of NHE produced greater adaptations in soccer players architectural properties.

METHODS

The PRISMA 2020 guideline was used for reporting the present systematic review with meta-analysis for search procedures, study selection, data collection, and analysis.[38,39] The present study was registered on the International Prospective Register of Systematic Reviews (PROSPERO; registration number: CRD42022361415). A protocol for the present systematic review was not prepared previously.

Literature Search and Data Sources

Five databases were used for the search: PubMed, SPORTDiscus, Web of Science, PsycInfo, and CINAHL. The search included studies published up to January 2, 2024. The search strategy was: (football OR soccer OR player*) AND (exercise OR training OR strength) AND ("biceps femoris" OR hamstring*) AND ("muscle architecture" OR architectural OR "pennation angle" OR "fascicle length" OR "muscle thickness" OR "muscle stiffness" OR "cross-sectional area"). All citations were entered into the Rayyan Intelligent Systematic Review tool. Duplicates were excluded automatically, and the remaining studies were selected by title and abstract according to eligibility criteria. The reference lists of the selected studies were reviewed to find other potentially eligible studies.

Inclusion and Exclusion Criteria

The PICOS framework (patient population, intervention, comparative controls, outcomes, study type) was applied to formulate eligibility criteria.[43] Studies were included if the following criteria were met: (1) patient population: all participants were soccer players (not beach soccer or futsal) involved in a competition (independently of the competitive level) and presented no injuries or no cardiovascular, metabolic, or musculoskeletal disorders and no history of doping or drug abuse, participants mean age was >16 years; (2) intervention: at least 1 group underwent a resistance training intervention based on lower limbs and resistance training interventions with hamstring exercises of at least 4 weeks[16]; (3) comparative controls: reporting pre-post intervention measurements, regardless of whether they compared with a control group or with another type of resistance training intervention; (4) outcomes: muscle architecture (ie, muscle thickness, fascicle length, pennation angle) of the biceps femoris long head was assessed through ultrasound images or MRI scans; (5) study design: randomized controlled trials, nonrandomized controlled trials, before-after (pre-post) studies or factorial study designs.[1]

The exclusion criteria were as follows: (1) players changing their usual nutrition for the intervention (ie, which could affect the muscle mass adaptations); (2) electrical stimulation was used during the resistance training intervention; (3) no full-text was available and/or the authors did not provide the necessary data.

Study Selection

The initial search was conducted by 1 researcher. After duplicates were removed, the same researcher performed the screening of the title and abstract of the papers extracted from the databases. Then, 2 researchers independently selected the included studies after reading the full text. If no agreement was reached, a third researcher intervened and settled the dispute.

Data Extraction

A researcher conducted the extraction of means and standard deviations and sample size from the selected studies, and another researcher confirmed the data extraction. If necessary, the corresponding author of the present study contacted the authors of the studies in which this information was not detailed explicitly. In addition, the extracted data included participant characteristics; duration of intervention; selection of exercise for resistance training interventions; competitive level of participants; the measurement technique of muscle architecture; and the intensity (ie, load), frequency, total volume (ie, repetitions), and degree of effort of the resistance training interventions.

Quality Assessment

The methodological quality and the risk of bias of the included studies were assessed using the Tool for the assEssment of Study qualiTy and reporting in EXercise (TESTEX) scale, since it was specifically designed for exercise interventions.[48] Two authors independently assessed study quality using 5 questions (eligibility criteria, random allocation, allocation concealment, similar baseline groups, and blinding of all assessors) with 1 point for each question, and study reporting using 7 questions (outcome measures assessed in 85% of patients, intention-to-treat analysis, between-group comparisons, point and variability measures, activity monitoring in control groups, relative exercise intensity remained constant, and exercise volume and energy expenditure) to give a total of 15 points. Disagreements were resolved by a third researcher. The following criteria were used to verify the risk of bias and quality of the studies: high quality and low risk of bias, ≥10 points; moderate quality and risk of bias, 7 to 9 points; poor quality and high risk of bias, 1 to 6 points.[7]

Statistical Analysis

The software Review Manager (RevMan, Version 5.4, The Cochrane Collaboration, 2020) was used for statistical analyses. Effect sizes (ESs) between post- and pre-intervention measurements were assessed for each study using Hedges' *g* with an adjustment for small sample bias[23]:

$$ES = \frac{M_{post} - M_{pre}}{SD_{pooled}} \cdot \left(1 - \frac{3}{8n - 9}\right)$$

where n is the sample size, $M_{post} - M_{pre}$ is the mean difference between post- and pre-intervention outcomes, and SD_{pooled} is the pooled standard deviation, which was calculated with the following equation[23]:

$$SD_{pooled} = \sqrt{\frac{SD_{pre}^2 + SD_{post}^2}{2}}$$

ES was interpreted as small (0.1-0.3), medium (0.3-0.6), or large (>0.6).[6] Mean differences were weighted according to the inverse variance-weighted average method.[23] The CIs for the ES were computed at the 95% confidence level. We performed a randomized effect model in the analyses and heterogeneity among studies was assessed using I^2 statistics with I^2 values (ranging from 0% to 100%) considered low if I^2 was <25%, moderate between 25% and 50%, and high if I^2 was >50%.[17] Significance was set at $P < 0.05$.

Subgroup analyses were performed to evaluate the potential moderating variables. Regarding the measured outcomes, the cut-off point was established to distinguish heavy (≥85% RM) from lower (<85% RM) loads in terms of intensity. In the exercise selection variable, we aimed to evaluate the differences between those resistance training programs carried out primarily (≥50% of the training program) with hip-dominant exercises versus knee-dominant hamstring exercises due to the different muscle activation pattern produced in hamstring muscles.[35,50] In addition, we aimed to compare the NHE versus only onfield training due to the popularity of this exercise in training interventions in soccer players.[29,34] In regard to frequency of training, we aimed to compare the effects on muscle architecture of low frequency (1 day per week) versus higher frequency (≥2 days per week) of resistance training. Regarding the degree of effort, we aimed to compare the effects of training until muscle failure versus nonmuscle failure on muscle architecture. For volume variable, we analyzed the differences between high versus low volume of training based on the median of the volume (ie, repetitions) that the included resistance training interventions presented, since it is difficult to determine the cut-off point to establish what is high or low volume of training.

Sensitivity analyses were conducted omitting studies of low methodological quality to determine the robustness of the overall results.

RESULTS

Study Selection

Database search identified 275 results. After removing duplicates, a total of 168 studies were identified for title and abstract selection. This screening resulted in a total of 12

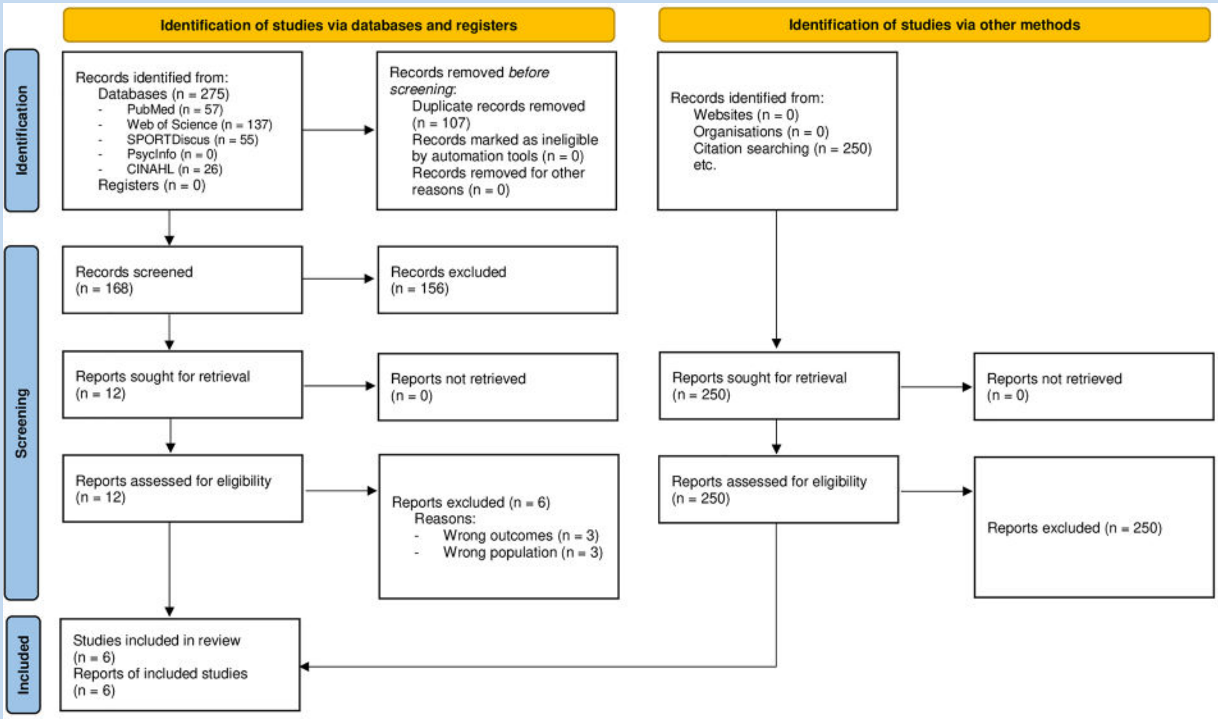

Figure 1. Flow chart of the study selection process.

articles, of which 6 finally entered the systematic review.[25,29,34,36,47,54] In addition, 250 studies from the reference lists were screened, but none met the eligibility criteria (Figure 1).

Characteristics of Studies and Interventions

The 6 included studies had at least 1 resistance training group. Table 1 shows the characteristics of the included studies. No studies exceeded a mean of >2 days per week of resistance training. Consequently, the comparison between low frequency versus higher frequency was actually a comparison between training 1 day per week versus training 2 days per week. Only 1 study included female soccer players,[54] who accounted for a total of 17 (11.2%) of the 152 players analyzed. The same study had a control group that served only as a measure of ultrasound reliability. The mean age of the participants ranged from 16.65 to 24 years.[47,54] One study included only a resistance training group,[47] while 3 studies included 2 groups (2 resistance training groups or a control group),[25,34,54] and 2 studies included 3 groups (2 intervention groups and 1 control group).[29,36] Regarding measurement technique, it is important to note that all the included studies assessed muscle architecture through ultrasound images. Two studies conducted a randomized controlled trial,[29,34] 2 studies conducted a block randomization because the sample belonged to 2 different clubs,[36] or to achieve the same characteristics of strength, fascicle length, and competition level.[25]

Table 2 shows the characteristics of the resistance training interventions and the main results of the included studies. The duration of the interventions ranged from 6 to 12 weeks. The intensity (ie, resistance of the exercise) of the resistance training groups was the bodyweight due to the exercise (ie, NHE) performed in the interventions. Only 1 study performed a hip-dominant exercise (ie, stiff-leg deadlift),[25] whereas another included a training group whose intervention was based on acceleration and sprint drills.[36] The median of the training volume of the included interventions was 290 repetitions across the training program.

It was possible to analyze the effects of the NHE versus control groups, the effects of low frequency versus higher frequency and the effects of high volume and low volume of training. It is important to clarify that control groups underwent a training intervention based on field exercises, but this intervention was not expected to alter the outcome measures adopted. Consequently, control groups should be understood as groups that perform only onfield training. The effects of different intensities and hip-dominant versus knee-dominant hamstrings on biceps femoris long head architecture were not able to be analyzed because all the included studies performed the NHE in the resistance intervention, so the relative load was the same in all the interventions (ie, bodyweight). The degree of effort was also not possible to analyze because no study conducted training until muscle failure or the degree of effort was not reported.

A total of 8 resistance training groups were analyzed for NHE versus control groups on muscle thickness, 11 for fascicle length, and 8 for pennation angle. A total of 7 resistance training groups were analyzed for low frequency versus higher frequency on muscle thickness, 10 for fascicle length, and 7 for pennation angle.

Table 1. Characteristics of the included studies

Study (Year)	Training Group	n	Competitive Level	Measurement Technique	Measured Outcomes
Lacome et al[25] (2020)	(1) High volume	10	Elite academy	Ultrasound	FL
	(2) Low volume	9			
Lovell et al[29] (2020)	(1) NHE before	10	Amateur	Ultrasound	MT, FL, PA
	(2) NHE after	14			
	(3) Control	11			
Medeiros et al[34] (2020)	(1) Low frequency	15	National Premier Division	Ultrasound	MT, FL, PA
	(2) High frequency	17			
Mendiguchia et al[36] (2020)	(1) NHE group	12			
	(2) Sprint group	10	Elite Division of Football Association of Porto	Ultrasound	MT, FL, PA
	(3) Soccer group	10			
Siddle et al[47] (2022)	(1) NHE group	17	Elite Academy	Ultrasound	MT, FL, PA
Vianna et al[54] (2021)	(1) NHE group	17	Group 1: Professional Group 2: Amateur	Ultrasound	FL

FL, fascicle length; MT, muscle thickness; NHE, Nordic hamstring exercise; PA, pennation angle.

Study Methodological Quality Assessment and Evaluation of the Potential Risk of Bias

The TESTEX scale was used to evaluate the quality of the included studies and the potential risk of bias. According to this scale and the aforementioned qualitative assessment,[7] the methodological quality of the included studies (Table 3) was high, suggesting a low risk of bias (11.33 ± 1.89). Two studies did not randomize intervention or control groups due to having only 1 group in the study due to the nature of the participants (elite male academy soccer players), which makes it impossible to isolate a group as a control group without training intervention,[47] or due to the different competitive level of the recruited teams. Half of the included studies reported that all assessors were blinded.[34,36,54]

Pooled Data

Pooled data (ie, forest plots) are presented in the Online Appendix.

Sensitivity Analyses

Sensitivity analyses were not necessary as no study had low methodological quality and high risk of bias.

DISCUSSION

The present study assessed the effects of key resistance training variables, including intensity, training frequency, degree of effort, and volume on biceps femoris muscle architecture in soccer players. Although exercise selection was also considered, the included studies focused primarily on the NHE, with 1 exception: a study that included both an NHE group and a sprint group, in addition to the soccer group.[36] As a result, it was not possible to analyze the effects of hip-dominant versus knee-dominant exercises, meaning the results presented here reflect mainly the effects of the NHE. The results of the present systematic review showed that muscle thickness had a nonsignificant increase, pennation angle had a nonsignificant decrease after different NHE programs, whereas the fascicle length was significantly greater. As expected, only onfield training did not show significant pre-post adaptations. A previous meta-analysis showed similar results in healthy adults,[16] demonstrating that eccentric exercise such as the NHE produces increases in muscle thickness and fascicle length, while pennation angle decreases after this type of exercise. Consequently, the results of the present systematic review appear to be consistent with previous findings.

Table 2. Characteristics of the resistance training groups and main results

Study (Year)	Duration, Weeks	Exercise Selection	Load/ Intensity	Frequency, Days per Week	Degree of Effort	Total Volume, Repetitions	Main Intragroup Results	Main Intergroup Results
Lacome et al[25] (2020)	6	NHE, stiff-leg deadlift	NHE, BW; Stiff-leg deadlift, 10 kg	1	Submaximal	High volume group, 240; low volume group, 60	High volume group, ↑FL; low volume group, ↑FL	No between-group differences
Lovell et al[29] (2020)	12	NHE	BW	2	Submaximal	684	NHE after, ↑MT, ↑PA; NHE before, ↑PA	MT, NHE after > NHE before = Control
Medeiros et al[34] (2020)	8	NHE	BW	High frequency, 2; low frequency, 1	Submaximal	High frequency, 456; low, frequency, 228	High frequency, ↑MT, ↑FL; low frequency, ↑MT, ↑FL	No between-group differences
Mendiguchia et al[36] (2020)	6	NHE, sprint	NHE, BW; sprint, from BW to +70 %BW	NHE group, 2.5; sprint group, 2	Submaximal	NHE: 340	NHE, ↑FL, ↑PA; sprint, ↑FL	FL, Sprint > NHE > Control; PA, NHE > Sprint = Control
Siddle et al[47] (2022)	8	NHE	BW	1.25	Submaximal	144	Nonsignificant changes	-
Vianna et al[54] (2021)	8	NHE	BW	2	Submaximal	456	↑FL	-

Where exercise selection, intensity, or frequency for each group is not described but results are separated by groups, both groups had the same characteristics in terms of that variable. BW, bodyweight; FL, fascicle length; MT, muscle thickness; NHE, Nordic hamstring exercise; PA, pennation angle.

Table 3. Methodological quality and risk of bias assessment of the included studies according to the TESTEX scale

TESTEX Scale Item	Lacome et al[25] (2020)	Lovell et al[29] (2018)	Medeiros et al[34] (2020)	Mendiguchia et al[36] (2020)	Siddle et al[47] (2022)	Vianna et al[54] (2021)
Eligibility criteria	1	1	1	1	1	1
Random allocation	1	1	1	1	-	-
Allocation concealment	1	1	1	1	-	-
Similar baseline groups	1	1	1	1	-	1
Blinding of all assessors	-	-	1	1	-	1
Outcome measures assessed in 85% of patients	2	2	2	1	3	3
Intention-to-treat analysis	1	1	1	1	1	1
Between-group comparisons	2	2	2	2	-	-
Point and variability measures	1	1	1	1	1	1
Activity monitoring in control groups	0	1	0	1	0	0
Relative exercise intensity remained constant	0	1	1	1	1	1
Exercise volume and energy expenditure	1	1	1	1	1	1
Total	11	13	13	13	8	10

These results could have an important impact on injury prevention, especially due to the relationship between fascicle length and injury risk.[3,52,53] In elite soccer players, short biceps femoris fascicles have been shown to increase the risk of hamstring injuries,[52] therefore increasing the length of the biceps femoris fascicle through eccentric exercise such as the NHE could reduce the incidence of injury.[29,34,52] One of the theories proposed most often to explain the relationship between muscle fascicle length and risk of injury is that the fascicle length reflects the number of sarcomeres in series, but only 1 study shows that the number of sarcomeres in series is not increased after eccentric exercise in humans.[41] Nonetheless, the present study should be interpreted with caution, since the assessment of the number of sarcomeres is based on estimation that may be misleading.[11,12] However, as previously stated,[22] the present study has challenged the traditional recognition of the striation/sarcomere pattern in skeletal muscles, highlighting the complex interaction between serial sarcomere adaptation, sarcomere length, sarcomere length nonuniformity, and muscle properties. Therefore, it appears to present a well-constructed counterargument to eccentric-induced serial sarcomerogenesis. In this line, further research in the future is necessary for a better understanding of the adaptations in serial sarcomeres with more accurate methods. However, muscle excursion seems to be a very important factor, since muscle fiber length allows a greater excursion of a muscle and the length-tension relationship is optimized, thus increasing the capacity of producing strength at long muscle positions.[28,55] In this line, it is important to highlight that the most common injury mechanism of biceps femoris long head is during the late swing phase of sprinting,[24] in which this muscle suffers the largest peak muscle-tendon strain (greater than semitendinosus and semimembranosus) during the sprinting gate cycle.[45]

Recent studies have shown that method of estimation of fascicle length using prediction equations is not very accurate[12,13] but is the most common measurement method used in studies evaluating muscle architecture using ultrasound imaging.[52,53] Measurement through prediction equations, given the reduced field of view and resulting from the narrow width of the transducer, is not a very accurate method because muscle thickness is not constant along the muscle length and could follow a nonlinear pattern.[12] Moreover, the fascicle is frequently curved,[12] which casts doubt on the accuracy of estimation through prediction equations assuming a straight-line fascicle. This limitation can lead to greater fascicle estimations, a restricted region of interest analyzed, questionable mathematical extrapolations, and the omission of fascicle and aponeurosis 3-dimensional (3-D) curvature.[9,11,40] To shed some light on this issue, Núñez et al[37] assessed the biceps femoris long head architectural properties through the extended field of view technique to obtain panoramic images. Since all included studies in the present systematic review analyzed the length of the fascicles with prediction equations, it is recommended that future studies measure the muscle fascicle through images in which the fascicle is viewed in its entirety. Therefore, results on the fascicle length reported in this study should be analyzed with caution because validity of the measurements could affect them.

It is important to note that only 1 study included a hip-dominant exercise (ie, the bilateral stiff-leg deadlift) in the resistance training intervention.[25] This fact may be surprising due to the greater and selective activation of the long head of the biceps femoris in hip-dominant exercises than in knee-dominant hamstrings exercises.[35,50] Another key component in reducing injury risk is the execution of exercises at high intensity, and therefore at high speed,[30-32] due to the injury mechanism of the hamstrings, which suffer injuries in actions of high intensity such as sprinting.[8,15,18] Therefore, the use of hip-dominant exercises and especially those performed at high velocities could produce greater improvements in muscle architecture and thus reduce hamstring injury risk. Future research could examine the effects of hip-dominant exercises versus knee-dominants in muscle architecture.

In the comparison between low training frequency (ie, 1 day per week) and higher training frequency (ie, ≥2 days per week), higher training frequency was limited to 2 training sessions per week due to the characteristics of the included studies (Table 2). Training twice a week did not result in significantly better adaptations on muscle architecture compared with training once a week. Nonetheless, it is important to highlight that higher frequency of training showed greater ES in all measured variables (ie, muscle thickness, fascicle length, and pennation angle), especially in muscle thickness and fascicle length. Nevertheless, strength adaptations were not the objective of the present study, but it has been demonstrated that even training 3 times per week induces similar strength adaptations than training once a week, with significant differences in structural adaptations.[46] The study by Medeiros et al[34] compared the strength and architectural adaptations with a training frequency of once a week or twice a week and showed significant differences only in the concentric peak torque, whereas the eccentric peak torque, the conventional hamstring-to-quadriceps ratio, and functional hamstring-to-quadriceps ratio did not show significant differences, with no significant differences in muscle architecture. Therefore, it seems that training twice a week did not produce different strength and structural adaptations than training once a week, whereas training 3 times per week could produce significantly higher structural adaptations. This could have important implications for injury prevention due to the aforementioned relationship between muscle structural adaptations and injury risk. Thus, strength and conditioning coaches should assess whether they are interested in introducing 1 more day of training per week given the minimal differences in structural adaptations, and apparently no difference in strength levels. Nonetheless, it is important for coaches to consider that muscle thickness and fascicle length only improved significantly with 2 training sessions per week. They have to make this decision (ie, to implement 1 or 2 days of training) based on availability during the week and the fatigue that training could induce. To equalize both structural and strength adaptations, it seems that equalizing training volume is an effective strategy, despite the training frequency being different.[21] In this line, high volume (ie, >290 repetitions along the training program) showed significant increases in fascicle length, whereas low volumes of training (ie, <290 repetitions) did not show significant differences. Nonetheless, it is important to highlight that the duration of the training program in weeks could lead to different training density (ie, repetitions per week). In this line, the minimal dose in terms of training weeks for the high-volume group was that performed by Mendiguchia et al,[36] with only 6 weeks of training and even showing the greatest ES, whereas the study conducted by Lovell et al[29] performed 12 weeks of training and also showed one of the greatest ESs. On the other hand, the interventions included in the low-volume group ranged from 6 to 8 weeks (ie, with <290 repetitions along the training program), so the duration of the training program could not be as determinant as the number of repetitions performed. Surprisingly, the training density, defined as the number of repetitions performed per week, reached 57 repetitions per week across all high-volume groups, accumulating over 290 repetitions throughout the training program. In contrast, the low-volume groups performed <40 repetitions per week. Therefore, when designing resistance training programs aimed at fascicle lengthening through the NHE, practitioners should aim for a total volume exceeding 290 repetitions, ensuring a minimum weekly density of 57 repetitions. Consequently, training frequency, volume of work, and density should be taken into account to design the training program. To ensure that significant increases in fascicle length are achieved, and thus the risk of injury is reduced, we recommend 2 days of training and >290 repetitions, with 57 repetitions per week across the training program with at least 6 weeks of training.

It is important to note that the present study has limitations, so our results must be interpreted with caution. The first and main limitation is the 2-dimensional (2-D) assessment method for measuring fascicle length of the biceps femoris long head due to the aforementioned issues regarding the validity of the extrapolation method used in the included studies. These limitations include: (1) the reduced field of view, as the narrow width of the transducer restricts the observable area, potentially leading to overestimations of fascicle length and a limited region of interest, which may affect measurement accuracy; (2) the reliance on mathematical extrapolations from 2-D images, which may fail to adequately represent the complex 3-D structure of muscle fascicles; and (3) the omission of 3-D curvature, as 2-D ultrasound methods do not account for the 3-D curvature of fascicles and aponeuroses, potentially introducing further inaccuracies. Another important issue is that the results of the present study should not be extrapolated directly to dynamic tasks, since the assessment of the improvements in fascicle length were conducted in a static position. As previously stated,[36] more research is necessary to thoroughly understand the mechanisms driving these architectural changes (muscle-tendon interaction) and to verify the proposed hypotheses in dynamic, rather than just isolated and static, movements. In this line, this issue is more important to contrast given that the biceps femoris long head length is determined primarily by the tendinous tissue during dynamic tasks such as the NHE and is less influenced by fascicles, which operate more isometrically in knee-dominant exercises.[27] An additional limitation is that soccer players from the different included studies did not have the same competitive level and thus their training status could be very different. Another limitation is the different volume in the resistance training programs included in the present systematic review (Table 2), because those training programs with higher volumes of training are the ones that can achieve the greatest adaptations. Another limitation is the wide range of weeks in which training programs were carried out (ie, 6 to 12 weeks), so it was difficult to give advice about the training program duration. In addition, this systematic review did not compare effects of the resistance training variables against similar control groups due to the analysis employed in this study (pre-post standardized mean difference) and the limited number of control groups (ie, 2). Given this limitation, the analysis used in the present study allows a comparison between intervention groups and control groups (test for subgroup differences) that would not allow an analysis to be carried out using the mean difference between intervention and control groups. Also, 6 studies may be too few to draw firm conclusions. This is why some of the desired objectives of the present systematic review could not be met. In addition, only 1 study included female soccer players, so the results of the present study are not conclusive in female players. It is important to note that meta-regression was intended to be performed to understand the variables that better explained the ES and to potentially explain causes of high heterogeneity together with analyses of the variables of resistance training (eg, wide range of intensities, volumes of training, etc). However, <10 studies were included in each comparison, so meta-regression could not be performed.[5,42] Finally, the evaluators of the included studies were not blinded in half of the included studies, so there is a risk of implicit assessment bias in these studies.

CONCLUSION

This systematic review showed that resistance training programs based on the NHE are effective strategy to enhance the length of the biceps femoris fascicle in soccer players, although muscle thickness and pennation angle showed a nonsignificant increase and a nonsignificant decrease, respectively. Training once or twice a week showed no significant differences in muscle thickness, fascicle length, or pennation angle adaptations, but training twice a week did maximize architectural adaptations. More than 290 NHE repetitions in a period of 6 to 12 weeks with at least 57 repetitions per week induced significant increases in fascicle length.

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REFERENCES

1. Aggarwal R, Ranganathan P. Study designs: part 4 - interventional studies. *Perspect Clin Res.* 2019;10(3):137-139.
2. Al Attar WSA, Soomro N, Sinclair PJ, Pappas E, Sanders RH. 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 Med.* 2017;47(5):907-916.
3. Blazevich AJ, Cannavan D, Coleman DR, Horne S. Influence of concentric and eccentric resistance training on architectural adaptation in human quadriceps muscles. *J Appl Physiol (1985).* 2007;103(5):1565-1575.
4. Cadu J-P, Goreau V, Lacourpaille L. A very low volume of Nordic hamstring exercise increases maximal eccentric strength and reduces hamstring injury rate in professional soccer players. *J Sport Rehabil.* 2022;31(8):1061-1066.
5. Cumpston M, Li T, Page MJ, et al. Updated guidance for trusted systematic reviews: a new edition of the Cochrane Handbook for Systematic Reviews of Interventions. *Cochrane Database Syst Rev.* 2019;10(10):ED000142.
6. Cohen J. *Statistical Power Analysis for the Behavioral Sciences.* Abingdon-on-Thames: Routledge; 2013.
7. Corso M, Miarka B, Figueiredo T, Bragazzi N, Carvalho D, Dias I. Effects of aerobic, strength, and combined training during pregnancy in the blood pressure: a systematic review and meta-analysis. *Front Physiol.* 2022;13:916724.
8. Danielsson A, Horvath A, Senorski C, et al. The mechanism of hamstring injuries - a systematic review. *BMC Musculoskelet Disord.* 2020;21(1):641.
9. Dick TJM, Wakeling JM. Geometric models to explore mechanisms of dynamic shape change in skeletal muscle. *R Soc Open Sci.* 2018;5(5):172371.
10. Ekstrand J, Bengtsson H, Waldén M, Davison M, Khan KM, Hägglund M. Hamstring injury rates have increased during recent seasons and now constitute 24% of all injuries in men's professional football: the UEFA Elite Club Injury Study from 2001/02 to 2021/22. *Br J Sports Med.* 2023;57:292-298.
11. Franchi MV, Fitze DP, Raiteri BJ, Hahn D, Spörri J. Ultrasound-derived biceps femoris long head fascicle length: extrapolation pitfalls. *Med Sci Sports Exerc.* 2020;52(1):233-243.
12. Franchi MV, Raiteri BJ, Longo S, Sinha S, Narici MV, Csapo R. Muscle architecture assessment: strengths, shortcomings and new frontiers of in vivo imaging techniques. *Ultrasound Med Biol.* 2018;44(12):2492-2504.
13. Freitas SR, Marmeleira J, Valamatos MJ, Blazevich A, Mil-Homens P. Ultrasonographic measurement of the biceps femoris long-head muscle architecture. *J Ultrasound Med.* 2018;37(4):977-986.
14. Fukunaga T, Kawakami Y, Kuno S, Funato K, Fukashiro S. Muscle architecture and function in humans. *J Biomech.* 1997;30(5):457-463.
15. Garcia AG, Andrade R, Afonso J, Runco JL, Maestro A, Espregueira-Mendes J. Hamstrings injuries in football. *J Orthop.* 2022;31:72-77.
16. Gérard R, Gojon L, Decleve P, Van Cant J. The effects of eccentric training on biceps femoris architecture and strength: a systematic review with meta-analysis. *J Athl Train.* 2020;55(5):501-514.
17. Grant J, Hunter A. Measuring inconsistency in knowledgebases. *J Intell Inf Syst.* 2006;27:159-184.
18. Gronwald T, Klein C, Hoenig T, et al. Hamstring injury patterns in professional male football (soccer): a systematic video analysis of 52 cases. *Br J Sports Med.* 2022;56(3):165-171.
19. Hägglund M, Waldén M, Ekstrand J. Injuries among male and female elite football players. *Scand J Med Sci Sports.* 2009;19(6):819-827.

20. Hägglund M, Waldén M, Magnusson H, Kristenson K, Bengtsson H, Ekstrand J. Injuries affect team performance negatively in professional football: an 11-year follow-up of the UEFA Champions League injury study. *Br J Sports Med*. 2013;47(12):738-742.
21. Hamarsland H, Moen H, Skaar OJ, Jorang PW, Rødahl HS, Rønnestad BR. Equal-volume strength training with different training frequencies induces similar muscle hypertrophy and strength improvement in trained participants. *Front Physiol*. 2022;12:789403.
22. Herzog W, de Brito Fontana H. Does eccentric exercise stimulate sarcomerogenesis? *J Sport Health Sci*. 2022;11(1):40-42.
23. Higgins JPT, Thomas J, Chandler J, et al. *Cochrane Handbook for Systematic Reviews of Interventions*. New York: John Wiley & Sons; 2019.
24. Huygaerts S, Cos F, Cohen DD, et al. Mechanisms of hamstring strain injury: interactions between fatigue, muscle activation and function. *Sports*. 2020;8(5):65.
25. Lacome M, Avrillon S, Cholley Y, Simpson BM, Guilhem G, Buchheit M. Hamstring eccentric strengthening program: does training volume matter? *Int J Sports Physiol Perform*. 2020;15(1):81-90.
26. Lauersen JB, Bertelsen DM, Andersen LB. The effectiveness of exercise interventions to prevent sports injuries: a systematic review and meta-analysis of randomised controlled trials. *Br J Sports Med*. 2014;48(11):871-877.
27. Li C, Liu Y. Regional differences in behaviors of fascicle and tendinous tissue of the biceps femoris long head during hamstring exercises. *J Electromyogr Kinesiol*. 2023;72:102812.
28. Lieber RL, Ward SR. Skeletal muscle design to meet functional demands. *Philos Trans R Soc B Biol Sci*. 2011;366(1570):1466-1476.
29. Lovell R, Knox M, Weston M, Siegler JC, Brennan S, Marshall PWM. Hamstring injury prevention in soccer: before or after training? *Scand J Med Sci Sports*. 2018;28(2):658-666.
30. Malone S, Roe M, Doran DA, Gabbett TJ, Collins K. High chronic training loads and exposure to bouts of maximal velocity running reduce injury risk in elite Gaelic football. *J Sci Med Sport*. 2017;20(3):250-254.
31. McBurnie AJ, Harper DJ, Jones PA, Dos'Santos T. Deceleration training in team sports: another potential 'vaccine' for sports-related injury? *Sports Med*. 2022;52(1):1-12.
32. McCall A, Pruna R, van der Horst N, et al. Exercise-based strategies to prevent muscle injury in male elite footballers: an expert-led Delphi survey of 21 practitioners belonging to 18 teams from the Big-5 European Leagues. *Sports Med*. 2020;50:1667-1681.
33. McQuilliam SJ, Clark DR, Erskine RM, Brownlee TE. Mind the gap! A survey comparing current strength training methods used in men's versus women's first team and academy soccer. *Sci Med Footb*. 2022;6(5):597-604.
34. Medeiros TM, Ribeiro-Alvares JB, Fritsch CG, et al. Effect of weekly training frequency with the Nordic hamstring exercise on muscle-strain risk factors in football players: a randomized trial. *Int J Sports Physiol Perform*. 2020;15(7):1026-1033.
35. Mendez-Villanueva A, Suarez-Arrones L, Rodas G, et al. MRI-based regional muscle use during hamstring strengthening exercises in elite soccer players. *PLoS One*. 2016;11(9):e0161356.
36. Mendiguchia J, Conceição F, Edouard P, et al. Sprint versus isolated eccentric training: comparative effects on hamstring architecture and performance in soccer players. *PLoS One*. 2020;15(2):e0228283.
37. Núñez FJ, Martínez JC, Overberg JA, Torreno N, Suarez-Arrones L. Hamstring muscle architecture and myotonometer measurements in elite professional football players with a prior strained hamstring. *Biol Sport*. 2023;40(1):93-99.
38. Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *Int J Surg*. 2021;88:105906.
39. Page MJ, Moher D, Bossuyt PM, et al. PRISMA 2020 explanation and elaboration: updated guidance and exemplars for reporting systematic reviews. *BMJ*. 2021;372:n160.
40. Pimenta R, Blazevich AJ, Freitas SR. Biceps femoris long-head architecture assessed using different sonographic techniques. *Med Sci Sports Exerc*. 2018;50(12):2584-2594.
41. Pincheira PA, Boswell MA, Franchi MV, Delp SL, Lichtwark GA. Biceps femoris long head sarcomere and fascicle length adaptations after 3 weeks of eccentric exercise training. *J Sport Health Sci*. 2022;11(1):43-49.
42. Ramirez-Campillo R, García-Hermoso A, Moran J, Chaabene H, Negra Y, Scanlan AT. The effects of plyometric jump training on physical fitness attributes in basketball players: a meta-analysis. *J Sport Health Sci*. 2022;11(6):656-670.
43. Saaiq M, Ashraf B. Modifying "Pico" question into "Picos" model for more robust and reproducible presentation of the methodology employed in a scientific study. *World J Plast Surg*. 2017;6(3):390-392.
44. Sánchez-Medina L, González-Badillo JJ. Velocity loss as an indicator of neuromuscular fatigue during resistance training. *Med Sci Sports Exerc*. 2011;43(9):1725-1734.
45. Schache AG, Dorn TW, Blanch PD, Brown NAT, Pandy MG. Mechanics of the human hamstring muscles during sprinting. *Med Sci Sports Exerc*. 2012;44(4): 647-658.
46. Schoenfeld BJ, Ratamess NA, Peterson MD, Contreras B, Tiryaki-Sonmez G. Influence of resistance training frequency on muscular adaptations in well-trained men. *J Strength Cond Res*. 2015;29(7):1821-1829.
47. Siddle J, Weaver K, Greig M, Harper D, Brogden CM. A low-volume Nordic hamstring curl programme improves change of direction ability, despite no architectural, strength or speed adaptations in elite youth soccer players. *Res Sports Med*. 2024;32(1):49-60.
48. Smart NA, Waldron M, Ismail H, et al. Validation of a new tool for the assessment of study quality and reporting in exercise training studies. *Int J Evid Based Healthc*. 2015;13(1):9-18.
49. Spineti J, Figueiredo T, Bastos DE, Oliveira V, et al. Comparison between traditional strength training and complex contrast training on repeated sprint ability and muscle architecture in elite soccer players. *J Sports Med Phys Fitness*. 2016;56(11):1269-1278.
50. Suarez-Arrones L, Núñez FJ, Lara-Lopez P, Di Salvo V, Méndez-Villanueva A. Inertial flywheel knee- and hip-dominant hamstring strength exercises in professional soccer players: muscle use and velocity-based (mechanical) eccentric overload. *PLoS One*. 2020;15(10):e0239977.
51. Suchomel TJ, Nimphius S, Stone MH. The importance of muscular strength in athletic performance. *Sports Medicine*. 2016;46(10):1419-1449.
52. 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):1524-1535.
53. Timmins RG, Shield AJ, Williams MD, Lorenzen C, Opar DA. Biceps femoris long head architecture. *Med Sci Sports Exerc*. 2015;47(5):905-913.
54. Vianna KB, Rodrigues LG, Oliveira NT, Ribeiro-Alvares JB, Baroni BM. A preseason training program with the Nordic hamstring exercise increases eccentric knee flexor strength and fascicle length in professional female soccer players. *Int J Sports Phys Ther*. 2021;16(2):459-467.
55. Winters TM, Takahashi M, Lieber RL, Ward SR. Whole muscle length-tension relationships are accurately modeled as scaled sarcomeres in rabbit hindlimb muscles. *J Biomech*. 2011;44(1):109-115.