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Changes in rectus femoris architecture induced by the reverse nordic hamstring exercises

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ABSTRACT

BACKGROUND: Injuries and mechanical stimuli alter the muscle architecture and, therefore, its function. The changes in the architecture of the Rectus Femoris (RF) induced by an eccentric training protocol with Reverse Nordic Hamstring exercises (RNHE) have never been studied. Therefore, the aim of the present study was to determine the architectural adaptations of the Rectus Femoris (RF) after an eccentric training with Reverse Nordic Hamstring exercises (RNHE), followed by a subsequent detraining period.

METHODS: The 26 subjects performed a first week of control, 8 weeks of eccentric training, concluding with a 4-week period of detraining. The architectural characteristics of the RF were evaluated using 2D ultrasound at rest (pretest - week 1), after the training (posttest - week 9), and at the end of the detraining period (retest - week 13).

RESULTS: At the end of the training period, a significant increase in the muscle fascicle length (FL) (t=-8.96, d=2.22, P< 0.001), muscle thickness (MT) (t=-8.76, d=2.219, P< 0.001), pennation angle (PA) (t=-9.83, d=2.49, P< 0.05) and cross-sectional area (CSA) (t=-13.06, d=3.06, P< 0.001) was observed. After the detraining period FL, MT, PA and CSA showed a significant decrease.

CONCLUSIONS: The eccentric training with RNHE may cause changes in the architectural conditions of RF, which, in addition, are also reversible after a 4-week detraining period. The adaptations produced by RNHE may have practical implications for injury prevention and rehabilitation programs, which include the changes in muscle architecture variables.

Keywords: muscle adaptation; quadriceps; reverse nordic hamstring exercise; ultrasound.

Introduction

Quadriceps muscle injuries occur frequently in sports activities that require repeated sprint efforts.[1-4] In addition, they cause a longer period of time off than hamstring and adductor muscle injuries,[4] and their recurrence rates are very high (17%). In the extensor muscle of the knee, Rectus Femoris (RF) is the most commonly injured muscle.[1,5,6] Woods *et al.* [7] reported that RF injuries occurred more frequently (29%) than in hamstrings (11%) and adductors (12%) during the pre-season period among 91 professional football teams in the UK.

Muscle injuries usually occur during the eccentric phase;[8,9] more specifically the RF, which, due to its biarticular nature, is at great risk during rapid movements such as accelerations, decelerations, changes of direction or when hitting moving targets. [10] Among the risk factors for injury, there is inadequate flexibility of the quadriceps,[11,12] its ability to generate eccentric strength[11] and the existence of previous injuries of this muscle or of the hamstrings. [13]

The architectural characteristics of the skeletal muscle, the pennation angle (PA), muscle thickness (MT), and fascicle length (FL) vary when it is subject to mechanical stimuli[14-18] determining to a great extent its ability to produce strength. [19] It is relevant to understand the nature of these variations, since they have an impact on the function and risk of muscle injury. [14,15,20]

The muscle architecture may be influenced by injuries, reducing FL and modifying PA, with respect to the uninjured contralateral muscles. [20-21] These changes alter muscle function, since longer fascicles are associated with a higher maximum contraction rate[19] and a lower injury rate.[20] Eccentric training has become an effective prevention method, [22-27] since it has proved its ability to increase strength and power values to a greater extent than concentric and isometric exercise. [28] It also led to architectural changes in skeletal muscle by increasing

FL. [17,29,30] These changes have proven to be reversible after a detraining period without eccentric mechanical stimuli. [29]

Although the mechanisms that focus on the effectiveness of eccentric training have not yet been fully understood[31] it has been proposed that serial sarcomere addition may at least partially explain a greater resistance to microtrauma and injury caused by muscle tension.[32] In this sense, it has been reported that shortened muscle fascicles were associated with an increased risk of muscle injury in athletes.[35] Self-loading exercises such as the Nordic curl have previously shown their potential to increase the fascicle length. [30,34,35]

Previous research studies have analyzed the architectural changes, but using isokinetic dynamometry. [28,17,29,36] The use of this equipment has important drawbacks for athletes, such as its limited accessibility due to the high cost and its complex handling. [36] In addition, its use is not feasible in large groups of athletes, because its use time consuming.[36] It may even be considered "non-functional" due to bearing little resemblance to actual sporting activities, given that it is used in a sitting position. [17,29,36] Therefore, given the simplicity in the application of the “Reverse Nordic Hamstring” exercise (RNHE) and its lower costs, it could be considered an alternative eccentric training systems for the quadriceps muscles in the daily practice routine of atlhletes.

RF is actively lengthened during hip extension and knee flexion, generating a greater change in length of the knee RF than the hip. [38] Thus, it could be speculated that RF is more dependent on the knee than the hip. [39] The eccentric RNHE for the quadriceps muscles is an “open kinetic chain stretch shortening cycle knee dominant exercise”,[39] which has shown its effectiveness in increasing the optimum length of the knee externsors by 6.5º.[40] RNHE present a simple learning technique, which is performed with the athlete’s body weight without requiring additional equipment or material and can easily be applied individually or in groups.

Due to the high incidence of the quadriceps injuries and specifically in the RF,[6] it is relevant to observe the changes that occur in its architecture after an eccentric loading training. Therefore, the objective is to check whether RNHE causes architectural changes in the RF muscle. It was hypothesized that eccentric exercise would cause significant changes in muscle fascicle length, muscle thickness, pennation angle and cross-sectional area.

Materials and methods

Participants

The study sample was made up of 26 men practicing recreational physical activity with no history of lower limb injury in the past 12 months and no previous experience in eccentric training (Table I). All participants provided written informed consent form before carrying out the protocol and the previous training session took place at the Faculty of Education and Sport Sciences, University of Vigo, Campus de Pontevedra, Spain. The ethical approval for the study was granted by the Autonomous Ethics Committee of Research in Galicia, Xunta de Galicia, General Secretariat, Ministry of Health (Spain), in agreement with the provisions of the Declaration of Helsinki (Reference number: 2016/158).

[Table I]

Study Design

The study lasted 13 weeks. In week 1, participants undertook an initial assessment of the RF muscle architecture (pretest) and two sessions of familiarization with RNHE in order to ensure proper technical execution. Next, 8 weeks of eccentric training with RNHE were carried out. In week 9, the second assessment of the muscle architecture (posttest) was performed. Next, the participants underwent 4 weeks of detraining, avoiding any kind of mechanical stimulus of eccentric nature. At the end of week 13, the third assessment of the muscle architecture (retest) was carried out. All measurements were made at the same time of the day and under the same conditions for all participants.

Assessment of the RF architecture

The ultrasound measurement of the architectural characteristics was validated by their correlation with muscle measurements in cadavers.[20,41] The architectural properties of RF using this technique have previously been studied, proving its validity and applicability.[42,43] MT, PA, FL estimations and cross-sectional area (CSA) were determined from ultrasound images obtained along the longitudinal and cross-sectional axis of the muscle belly using B-mode ultrasound (12 Mhz frequency, 8 cm depth; 14 x 47 mm field of view) (GE Healthcare Vivid-i, Wauwatosa, USA).

All architectural measurements were performed after at least 5 minutes of inactivity, with the participant in prone decubitus position, with legs extended and relaxed muscles.[15]

The measurement site was the halfway point between the anterior superior iliac spine and the proximal margin of patella, along the line of the RF of the dominant leg.[42] Once the scanning site was determined in each participant, several anatomical landmarks were established (anterior superior iliac spine, greater trochanter, lateral condyle, medial condyle and proximal edge of patella) and photographs were taken in order to ensure reproducibility for future assessment sessions.

The participant's skin was covered with a conductive gel to obtain two types of images. The first image was taken by placing the ultrasound probe longitudinally and perpendicular to assess the rest of the architectural variables (PA, MT, FL) and the second was taken by aligning it sagittally and parallel to the anterior thigh to evaluate the CSA.[42-44] The probe was handled carefully by a sonographer (MFJ) to ensure minimal pressure and to not alter the accuracy of the measurements.[45]

After the scan, an analysis was carried out by means of an image processing software, Image J (National Institute of Health, USA). Following the procedure developed by Blazevich *et al.*[42] six points were digitized for each of the images on the longitudinal axis. The muscle thickness (MT) was defined as the distance between the superficial and intermediate aponeuroses of the RF. The pennation angle (PA) was delimited between the intermediate aponeurosis and the direction of a muscle fascicle previously identified in the image (Figure 1). The aponeurosis angle (AA) was determined as the angle between the line marked by the aponeurosis and a horizontal line drawn along the captured image.[41,42] Finally, the fascicle length (FL) was defined as the muscle fascicle length existing between both aponeuroses. Given that the total of the above-mentioned length cannot be observed in the field of view of the probe, an estimate was made using an equation validated by Kellis *et al.* [41] and Blazevich *et al.*[42]

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

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

[Figure 1]

The fascicle length was expressed in absolute terms (cm) and also relative to muscle thickness (RFL). The CSA assessment was performed on the sagittal images by observing the internal edges of the RF fascia, according to Bemben's procedure.[46]

All images were collected and analyzed by the same researcher (MFJ), who was blinded to the identity of the participants during the analysis. This researcher (MFJ), a member of the Spanish Society of Ultrasound in Physiotherapy (SEEFi). He had prior experience in the protocol and he was blinded to the identity of the participants during the analysis. He had been previously subject to an in-rater study to assess the reliability of the measure. Twelve healthy subjects participated, 5 2D-ultrasound images of the RF being performed in the same anatomical region in different sessions, obtaining reliable measurements of the different architectural variables (intraclass correlations> 0.90) within the ranges recommended by previous scientific studies.[47]

Eccentric "Reverse Nordic Hamstring" exercises

RNHE is an exercise designed to improve eccentric performance of the quadriceps[39,40] (Figure 2).

The athlete begins in a kneeling position, with the trunk in an upright position and fully aligned (Figure 2.a). At the time, the athlete slowly leans backward, maintaining the initial position through a controlled flexion of the knees (Figure 2. b). This fall is performed at the slowest speed possible in order to maximize the muscle load in the eccentric phase and to reach the maximum flexion point (Figure 2. c). All participants were instructed on the correct execution technique of RNHE two days before the training, in order to maximize its effectiveness. In addition, they were monitored during all sessions of the protocol.

[Figure 2]

Intervention

The participants performed a 8-week training protocol with RNHE aimed at promoting a progressive assimilation of the eccentric mechanical stimuli and reducing delayed onset muscle soreness. Each session lasted between 10 and 20 minutes, depending on the training volume of sets and repetitions according to the evolution of the program (Table II). All sessions were separated by at least 48 hours and preceded by 12-minute standardized warm-up self-loading exercises. This consisted of a 12-minute standardized warm up protocol, similar and prior to all the sessions comprising: 4 minutes of static bicycle, 4 minutes of lower limb self-loading exercises, and 4 minutes of lower limb dynamic stretching exercises.

Upon concluding the eccentric training phase, participants performed a 4-week detraining phase, avoiding any mechanical stimulus of similar nature.

[Table II]

Data Analysis

All statistical analyses were performed using the SPSS software, version 24.0 (IBM Corporation, Chicago, IL). The normal distribution of data was checked by means of the Shapiro-Wilk test and homoscedasticity through Levene’s test. The Greenhouse-Geisser correction was used when the test of sphericity was violated ($P<0.05$ for Mauchly’s test of sphericity). A repeated-measures ANOVA design was used to determine the training-induced changes in each of the muscle architecture variables (MT, PA, FL, RFL). The intrasubject variable was time (pretest, postest and retest). Partial eta squared (η_p^2) effect sizes for the time interaction effects were calculated. An effect of $\eta_p^2 \geq 0.01$ indicates a small, ≥ 0.059 a medium, and ≥ 0.138 a large effect, respectively.[48] Additionally, post-hoc t-tests with Bonferroni correction were conducted to compare variables from the different measurement pairs (pretest vs postest, postest vs retest). Significance was set at $P<0.05$ and Cohen's d effect was provided when necessary to quantify the effect size.[48]

Results

Taking into account the different variables of the assessed muscle architecture, the results are detailed below.

Fascicle length

FL is affected by the eccentric training protocol with functional RNHE, F (2-50) = 56.65, $P < 0.05$, = 0.69. The pairwise comparisons derived from the post hoc analysis showed a significant increase in the FL between pretest and posttest ($t = -8.96$, $d = 2.22$, $P < 0.001$) and a significant decrease between posttest and retest ($t = 8.12$, $d = 2.21$, $P < 0.001$).

Fascicle length relative to muscle thickness

The relationship between FL and MT is not affected by the eccentric training protocol with functional RNHE, F (1.16-28.88) = 0.66, $P > 0.05$, = 0.45. With regard to the pairwise comparisons derived from the post hoc analysis, there are no statistically significant differences in the RFL between pretest and posttest ($t = -0.43$, $P > 0.05$), and neither between posttest and retest ($t = 0.91$, $P > 0.05$).

Muscle thickness

MT is affected by the eccentric training protocol with functional RNHE, F (2-50) = 68.32, $P < 0.05$, = 0.73. Regarding the pairwise comparisons derived from the post hoc analysis, there is a significant increase in the MT between pretest and posttest (t = -8.76, d = 2.219, P < 0.001) and a significant decrease between posttest and retest (t = 10.0, d = 2.774, P < 0.001).

Pennation angle

PA is modified by the eccentric training protocol with functional RNHE, F (1.95-48.65) = 51.06, P < 0.05, = 0.67. With regard to the pairwise comparisons derived from the post hoc analysis, there is a significant increase in the PA between pretest and posttest (t = -9.83, d = 2.49, P < 0.05) and a significant decrease between posttest and retest (t = 4.48, d = 1.24, P < 0.05).

Cross-sectional area

The CSA is affected by the eccentric training protocol with functional RNHE, F (2-50) = 98.31, P < 0.05, = 0.80. In the pairwise comparisons derived from the post hoc analysis, a significant increase was noted in the CSA between pretest and posttest (t = -13.06, d = 3.06, P < 0.001) and a significant decrease between posttest and retest (t = -7.09, d = 1.96, P < 0.001).

The changes in LF, RFL, PA, MT and CSA during the training and detraining period are shown in table III.

[Table III]

Discussion

Our results indicate that the eccentric training with RNHE led to a significant increase of FL, PA, MT and CSA of the RF. In addition, a significant decrease of FL, PA, MT and CSA was found after the detraining period.

This study showed a significant increase of 9.59% in FL of the RF following an 8-week eccentric training protocol with RNHE, which was similar to the results found in previous studies. [29,30,34-36]

The differences in the duration of the intervention (from 6 to 12 weeks), in the training techniques (isokinetic dynamometry, NHE and RNHE) and in the involved muscle (Biceps Femoris (BF) and RF) may explain the percentage differences between the studies, although all are in agreement on the increase of FL after an eccentric strength training that could be due to the increase of sarcomeres in series.[32]

The results obtained provide more evidence on the fact that the eccentric stimuli behave differently than the concentric stimuli with respect to their incidence on the muscle fascicle length. The eccentric stimuli seem to cause its elongation while the concentric stimuli lead to its shortening.[29] Although the mechanisms that focus on eccentric training are not yet sufficiently understood, this elongation seems to be determined by a serial sarcomere addition. This mechanism is expected to reduce the tension experienced by the sarcomere at any given muscle length, and the risk of muscle injury is therefore minimized. [32] If future studies continue to confirm this trend, eccentric training could become a good tool to prevent injuries in muscle groups that tend to get injured by excessive elongation.

In the present study, 8 weeks of RNHE increased PA by 11.09% after the training period, which is similar to previously reportes results.[15,49] Baroni *et al.*[36] did not observe any significant changes after a 12-week eccentric isokinetic protocol. There is an apparent relationship between muscle size and angle of the fascicle[15], thus it seems that the increase in the PA is related to the increase in the MT and CSA. However, there seems to be no direct relationship between the PA and LF increase, since these two variables showed divergent behaviors in different muscle groups. Thus, the present study, along with earlier studies such as Blazevich et al.[15] on the VL obtained a PA and LF increase after a period of eccentric training, while others such as Timmins et al.[29] and Alonso-Fernandez et al. [34] on the BFlh or Alonso-Fernandez et al.[35] on the Semitendinosus muscle obtained PA decreases and LF increases after eccentric protocols. It seems that PA adapts according to the response to muscle hypertrophy and it could be therefore caused by the limited available space of the hypertrophied muscle, [15] and not so much by an increase in the fascicle length. But, further studies will be needed to observe the behavior of PA, as it seems to be closely linked to a particular muscle group and even to different parts thereof.[41]

A significant increase was observed in the MT of the RF after an eccentric training protocol, with results similar to those obtained by Baroni *et al*.[36] after an eccentric protocol using isokinetic equipment. Similarly, studies performed on the VL[15,36] observed a significant increase in MT after a period of eccentric strength training. At the same time, a significant increase of the CSA was detected, which coincides with previous studies on the RF[15,44] and in other muscle groups such as BF.[50]

The results also showed that the muscle architectural changes induced by the eccentric training with RNHE are reversed after a detraining period of 4 weeks, with a significant decrease in FL, PA, MT and CSA. These results are similar to those obtained in other studies.[16,29.] The study conducted by Blazevich et al.[15] showed how the architectural changes produced in the VL by a 10-week eccentric training protocol based on isokinetic dynamometry decreased after 5 weeks of detraining. More recently, Timmins et al.[29] also obtained a decrease in terms of the architectural changes produced by a 6-week eccentric training protocol with isokinetic dynamometry in the BFlh after a 4-week period of detraining. Using self-loading exercises such as the NHE in an 8-week training program, Alonso-Fernandez et al.[34] also obtained the same response pattern in the BFlh after 4 weeks of detraining. It seems that the structural changes induced in the muscles by a training protocol based on eccentric stimuli are reversible if these stimuli disappear. This fact seems to emphasize the need to perform a constant maintenance of the eccentric stimulus if the coaches want the effects to be maintained on a long-term basis in their athletes. However, the results do not allow us to know what would be the minimum volume of eccentric stimulus needed to maintain these architectural changes and extend them over time, something that in our opinion would be very interesting to address in future studies.

The results obtained seem to show that eccentric training and detraining have specific effects on muscle architecture. Previous studies[15,30] have suggested that architectural variables may have an influence on muscle injuries and, therefore, eccentric exercises could be a valuable tool for injury prevention and rehabilitation programs, although a greater number of studies should continue to delve into this relationship.

So far, these potential benefits of eccentric training were hardly transposed to the daily routine of athletes because they had been obtained with equipment and under conditions beyond their reach.[15,17,29,36]

In practical terms, and although further studies are needed, which should involve different populations of athletes, in order to obtain more generalizable conclusions about RNHE, we believe that 2 or 3 sessions of these exercises could be included once a week by trainers, always waiting at least 48 hours between sessions, and not at the same time as the specific workouts. In our view, its intensity could be enhanced by increasing the athlete’s weight with a weighted vest, when they are able to easily reach 10 repetitions per set, and with a proper execution technique.

This study had a few limitations, such as the use of 2D ultrasound for the architecture assessment requires to a certain degree an estimation, because FL is not entirely visible in the ultrasound image. Although the estimation equation used in this study was validated,[41] there is still a potential error that should be reduced in future works based on 2D ultrasound. On the other hand, only the RF architecture was evaluated, and considering that each muscle belly of the quadriceps has unique architectural characteristics, it would not be appropriate to generalize the results to all knee extensors. Further studies will be necessary to explore the conditions that may have an impact on this type of training to achieve lasting architectural effects in different populations of athletes.

Conclusions

The eccentric training of the quadriceps muscles with an exercise which can be easily applied (without additional equipment) and of short duration (between 10 and 15 minutes, 2-3 sessions per week) such as RNHE, has proven to be effective for modifying the variables of the muscle architecture of the RF. In addition, the adaptations produced by RNHE may have practical implications for injury prevention and rehabilitation programs.

REFERENCES

1. Orchard J, Seward H. Epidemiology of injuries in the Australian Football League seasons 1997–2000. Br J Sports Med 2002;36(1):39-44.
2. Balius R, Maestro A, Pedret C, Estruch A, Mota J, Rodríguez L, García P, Mauri E. Central aponeurosis tears of the rectus femoris: practical sonographic prognosis. Br J Sports Med 2009;43(11):818-24.
3. Brophy RH, Wright RW, Powell JW, Matava MJ. Injuries to kickers in American football: The National Football League experience. Am J Sports Med 2010;38(6):1166-73.
4. Ekstrand J, Hägglund M, Walden M. Epidemiology of muscle injuries in professional football (soccer). Am J Sports Med 2011;39(6):1226-32.
5. Ouellette H, Thomas BJ, Nelson E, Torriani M. Magnetic resonance imaging of rectus femoris origin injuries. Skeletal Radiol 2006;35:665-72.
6. Prior BM, Jayaraman RC, Reid RW, Cooper TG, Foley JM, Dudley GA, Meyer RA. Biarticular and monoarticular muscle activation and injury in human quadriceps muscle. Eur J Appl Physiol 2001;85(1-2):185-90.
7. Woods C, Hawkins RD, Maltby S, Hulse M, Thomas A, Hodson, A. The Football Association Medical Research Programme: an audit of injuries in professional football-analysis of hamstring injuries. Br J Sports Med 2004;38: 36-4.
8. Kellis E, Baltzopoulos V. Isokinetic eccentric exercise. Sports Med 1995;19(3):202-22.
9. Kujala UM, Orava S, Järvinen M. Hamstring injuries. Current trends in treatment and prevention. Sports Med 1997;23(6):397–404.
10. Brooks JHM, Fuller CW, Kemp SPT, Reddin DB. Incidence, risk and prevention of hamstring muscle injuries in professional rugby union. Am J Sports Med 2006;34(8):1297-306.

11. Fousekis K, Tsepis E, Poulmedis P. Intrinsic risk factors of non-contact quadriceps and hamstring strains in soccer: a prospective study of 100 professional players. Br J Sports Med 2011; 45(9):709-14.
12. Witvrouw E, Danneels L, Asselman P, D'Have T, Cambier D. Muscle flexibility as a risk factor for developing muscle injuries in male professional soccer players. Am J Sports Med 2003;31(1):41-6.
13. Orchard J. Intrinsic and extrinsic risk factors for muscle strains in Australian football. Am J Sports Med 2001;29(3):300-3.
14. Blazevich AJ. Effects of physical training and detraining, immobilisation, growth and aging on human fascicle geometry. Sports Med 2006;36(12):1003-17.
15. 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 2007;103(5):1565-75.
16. Seynnes OR, Maganaris CN, de Boer MD, di Prampero PE, Narici MV. Early structural adaptations to unloading in the human calf muscles. Acta Physiol (Oxf) 2008;193(3):265-74.
17. Potier TG, Alexander CM, Seynnes OR. Effects of eccentric strength training on biceps femoris muscle architecture and knee joint range of movement. Eur J Appl Physiol 2009;105(6):939-44.
18. Narici MV, Flueck M, Koesters A, Gimpl M, Reifberger A, Seynnes OR, Nirbauer J, Rittweger J, Mueller E. Skeletal muscle remodeling in response to alpine skiing training in older individuals. Scand J Med Sci Sports 2011;21(Supl 1):23-8.
19. Lieber RL, Ward SR. Skeletal muscle design to meet functional demands. Philos Trans R Soc Lond B Biol Sci 2011;366(1570):1466-76.
20. Timmins RG, Shield AJ, Williams MD, Lorenzen C, Opar DA. Biceps femoris long head

architecture: a reliability and retrospective injury study. Med Sci Sports Exerc 2015;47(5):905-13.

21. Van der Horst N, Smits DW, Petersen J, Goedhart EA, Backx FJG. The Preventive Effect of the Nordic Hamstring Exercise on Hamstring Injuries in Amateur Soccer Players: A Randomized Controlled Trial. Am J of Sports Med 2015;43(6):1316-23.
22. Askling C, Karlsson J, Thorstensson A. Hamstring injury occurence in elite soccer players after preseason strength training with eccentric overload. Scand J Med Sci Sports 2003;13(4):244-50.
23. Brooks JHM, Fuller CW, Kemp SPT, Reddin DB. Epidemiology of injuries in English professional rugby union: part 1 match injuries. Br J Sports Med 2005;39(10):757-766.
24. Brooks JHM, Fuller CW, Kemp SPT, Reddin DB. Epidemiology of injuries in English professional rugby union: part 2 training injuries. Br J Sports Med 2005;39(10):767-75.
25. Gabbe BJ, Branson R, Bennell KL. A pilot randomised controlled trial of eccentric exercise to prevent hamstring injuries in community-level Australian football. J Sci Med Sport 2006;9(1-2):103-9.
26. Arnason A, Anderson TE, Holme I, Engebretsen L, Bahr R. Prevention of hamstring strains in elite soccer: an intervention study. Scand J Med Sci Sports 2008;18(1):40-8.
27. Petersen J, Thorborg K, Bachmann M, Nielsen MB, Budtz-Jorgensen E, Hölmich P. Preventive Effect of Eccentric Training on Acute Hamstring Injuries in Men’s Soccer: A cluster-Randomized Controlled Trial. Am J Sports Med 2011;39(11):2296-303.
28. LaStayo PC, Woolf JM, Lewek MD, Snyder-Mackler L, Reich T, Lindstedt SL. Eccentric muscle contractions: their contribution to injury, prevention, rehabilitation, and sport. J Orthop Sports Phys Ther 2003;33(10):557-71.
29. Timmins RG, Ruddy JD, Presland J, Maniar N, Shield AJ, Williams MD, Opar DA. Architectural changes of the bíceps femoris long head after concentric or eccentric

training. Med. Sci. Sports Exerc 2016;48(3):499-508.

30. Bourne MN, Duhig SJ, Timmins RG, Williams MD, Opar DA, Al Najjar A, Kerr GK, Shield AJ. Impact of the Nordic hamstring and hip extension exercises on hamstring architecture and morphology: implications for injury prevention. Br J Sports Med 2017;51(5):469-77.
31. McHugh MP. Recent advances in the understanding of the repeated bout effect: the protective effect against muscle damage from a single bout of eccentric exercise. Scand J Med Sci Sports. 2003; 13(2):88-97.

32. Lynn R, Morgan DL. Decline running produces more sarcomeres in rat vastus intermedius muscle fibers than does incline running. J Appl Physiol 1994;77(3):1439-44.
33. Timmins RG, Bourne MN, Shield AJ, Williams MD, Lorenzen C, Opar DA. Short biceps femoris fascicles and eccentric knee flexor weakness increase the risk of hamstring injury in elite football (soccer): a prospective cohort study. Br J Sports Med. 2016;50(24):1524-35.

34. Alonso-Fernandez D, Docampo-Blanco P, Martinez-Fernandez J. Changes in muscle architecture of Biceps Femoris induced by eccentric strength training with Nordic Hamstring Exercise. Scand J Med Sci Sports 2018;28(1):88-94.
35. Alonso-Fernandez D, Gutiérrez-Sanchez A, Garcia-Remeseiro T. Effects of the Nordic Hamstring Exercise on the architecture of the semitendinosus. Isokinet Exerc Sci 2018;22(2):81-88.
36. Baroni BM, Geremia JM, Rodrigues R, De Azevedo Franke R, Karamanidis K, Vaz MA. Muscle architecture adaptations to knee extensor eccentric training: rectus femoris vs. vastus lateralis. Muscle Nerve 2013;48(4):498-506.

37. Sconce E, Jones P, Tuner E, Comfort P, Graham-Smith P. The validity of the nordic hamstring lower for a field-based assessment of eccentric hamstring strength. J. Sport Rehabil 2015;24(1):13-20.
38. Visser JJ, Hoogkamer JE, Bobbert MF, Huijing PA. Length and moment arm of human leg muscles as a function of knee and hip-joint angles. Eur J Appl Physiol Occup Physiol 1990;61(5-6):453-60.
39. Mendiguchia J, Alentorn-Geli E, Idoate F, Myer GD. Rectus femoris injuries in football: a clinically relevant review of mechanisms of injury, risk factors and preventive strategies. Br J Sports Med 2013;47(6):359-66.
40. Brughelli M, Mendiguchia J, Nosaka K, Idoate F, Arcos AL, Cronin J. Effects of eccentric exercise on optimum length of the knee flexors and extensors during the preseason in professional soccer players. Phys Ther Sport 2010;11(2):50-5.
41. Kellis E, Galanis N, Natsis K, Kapetanos G. Validity of architectural properties of the hamstring muscles: correlation of ultrasound findings with cadaveric dissection. J Biomech 2009;42(15):2549-54.
42. Blazevich AJ, Gill ND, Zhou S. Intra-and intermuscular variation in human quadriceps femoris architecture assessed in vivo. J Anat 2006;209(3):289-310.
43. Ema R, Wakahara T, Mogi Y, Miyamoto N, Komatsu T, Kanehisa H. In vivo measurement of human rectus femoris architecture by ultrasonography : validity and applicability. Clin Physiol Funct Imaging 2013;33(4):267-73.
44. Scanlon TC, Fragala MS, Stout JR, Emerson NS, Beyer KS, Oliveira LP, Hoffman JR. Muscle architecture and strength: Adaptations to short-term resistance training in older adults. Muscle and Nerve 2014;49(4):584-92.
45. Klimstra M, Dowling J, Durkin JL, MacDonald M. The effect of ultrasound probe orientation on muscle architecture measurement. J Electromyogr Kinesiol

2007;17(4):504-14.

46. Bemben MG. Use of diagnostic ultrasound for assessing muscle size. J Strength Cond Res 2002;16(1):103-8.
47. Narici MV, Binzoni T, Hiltbrand E, Fasel J, Terrier F, Cerretelli P. In vivo human gastrocnemius architecture with changing joint angle at rest during graded isometric contraction. J Physiol 1996;496(Pt 1):287-97.
48. Cohen J. Statistical power analysis for the vehavioural sciencies (2n ed). Hillsdale, NJ: Lawrance Erlbau;1988.
49. Seynnes OR, de Boer M, Narici MV. Early skeletal muscle hypertrophy and architectural changes in response to high-intensity resistance training. J Appl Physiol 2007;102(1):368-73.
50. Seymore KD, Domire ZJ, Devita P, Rider PM, Kulas AS. The effect of Nordic hamstring strength training on muscle architecture, stiffness, and strength. Eur J App Physiol 2017;117(5):943-953.

NOTES

Conflicts of interest.— "The authors certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript"

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TABLES

Table I.— *Characteristics of participants (mean ± standard error of the mean)*

N	Age (years old)	Weight (kg)	Height (m)
26	24.7 ± 2.9	77.6 ± 8.7	1.79 ± 0.08

Table II.—

Eccentric training progression with RNHE

Week	Number of sessions/week	Sets	Repetitions	Total number of repetitions	Rest between sets
1	2	2	6	24	2 min
2	2	2	8	32	2 min
3	3	3	6	54	2 min
4	3	3	8	72	2 min
5	3	3	8	72	2 min
6	3	3	10	90	2 min
7	3	3	10	90	2 min
8	3	3	10-12	90-108	2 min

Table III.— *Eccentric protocol with RNHE (n = 26)*

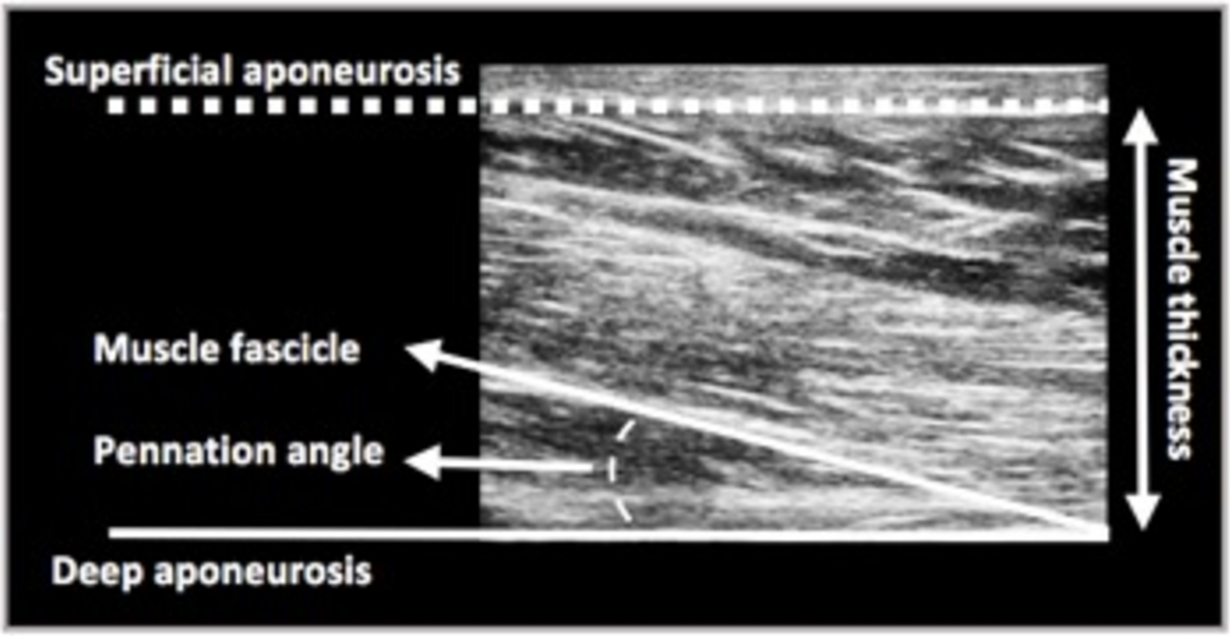
	M1 (Week 1)	M2 (Week 9)	M3 (Week 13)	% Change M1-M2	% Change M2-M3
FL (cm)	7.82±1.88	8.57±1.14**	8.18±1.35##	9.59	-4.55
RFL	3.70±0.35	3.74±0.38	3.72±0.34	1.08	-0.53
PA (º)	12.44±2.98	13.82±3.81*	13.26±2.02#	11.09	-4.05
MT (cm)	2.1±0.19	2.28±0.31**	2.18±0.26##	8.57	-4.38
CSA (cm2)	9.21±1.86	10.02±1.98**	9.61±1.37##	8.79	-4.26

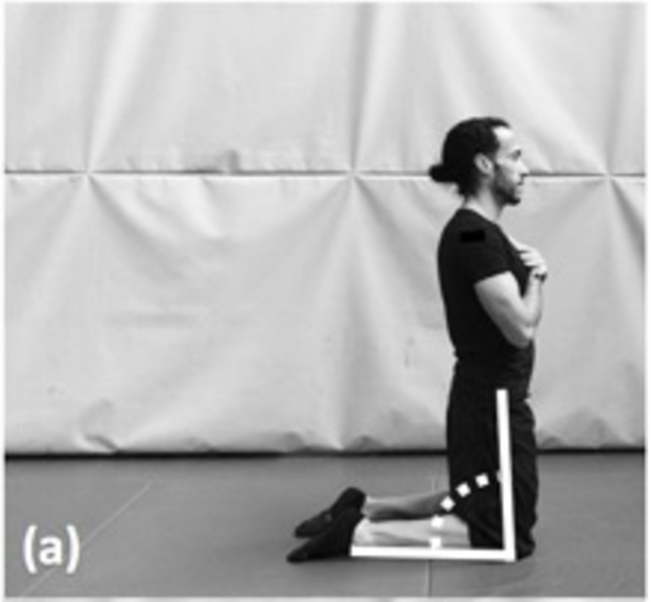
Table note: * = $P < .05$ vs M1, ** = $P < .001$ vs M1, # = $P < .05$ vs M2, ## = $P < .001$ vs M2.
FL = Fascicle lenght, RFL = fascicle lenght relative to muscle thickness, PA = pennation angle, MT = muscle thickness, CSA = cross-sectional area

TITLES OF FIGURES

Figure 1.— *Two-dimensional ultrasound image of the Rectus Femoris taken along the longitudinal axis of the anterior thigh.*

Figure 2.— *Reverse nordic hamstring exercise: (a) start, (b) midpoint, (c) end*


Superficial aponeurosis
Muscle fascicle
Pennation angle
Deep aponeurosis
Muscle thickness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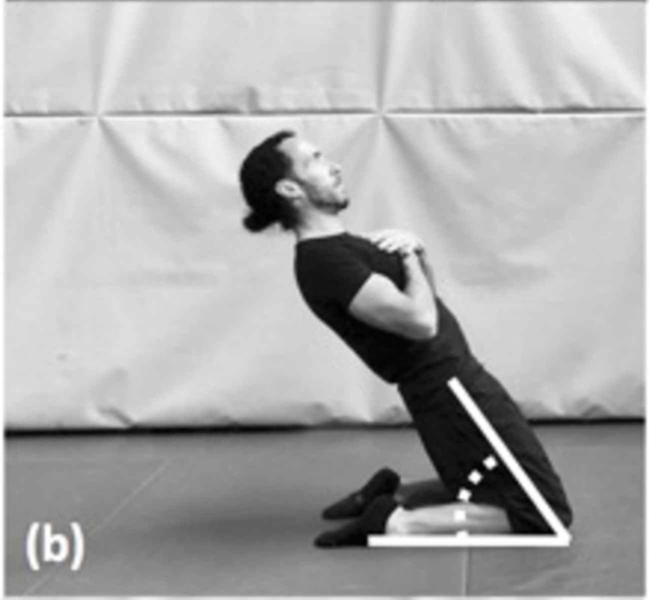
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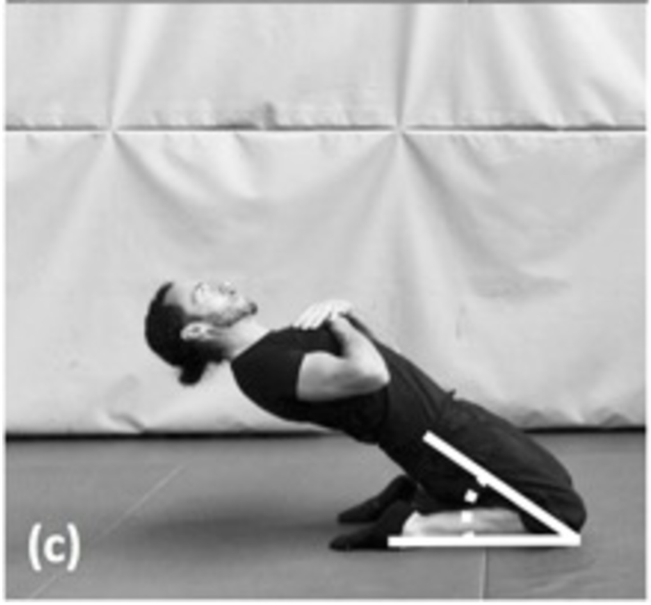
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