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RECTUS FEMORIS STRETCHING EFFECT ON ANTAGONIST MUSCLES STRENGTH IN HIGH-SPEED RUNNERS

EFECTO DEL ESTIRAMIENTO DEL RECTO FEMORAL SOBRE LA FUERZA DE LOS MÚSCULOS ANTAGONISTAS EN CORREDORES DE ALTA VELOCIDAD

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Abstract

Hamstring strain injury (HSI) is the most common injury in sports including high-speed running. Hamstring muscles main activation during sprinting is mainly in late swing phase in which they have to activate against hip flexors force. The purpose of this study was to analyse if rectus femoris (RF) muscle stretching produces immediate strength and activation increase in hamstrings muscles. An open-label, single-arm, control, pretest-posttest clinical trial was conducted. The study was carried out in the Aragonese centre of Sports and 16 (10 women and six men) high speed runners were recruited. Rectus femoris length and hamstrings isometric strength were registered as main outcomes and surface electromyography (sEMG), tensiomyography (TMG) variables and pelvic position were considered secondary outcomes: No differences were observed for any of the variables between baseline and control measurements. An increase in RF length (p<.002) and in hamstring isometric strength (p<.001) was registered between baseline and post-treatment measurements with a large effect size for both, 0.88 and 0.81 respectively measured by Cohen´s d.-test. It seems hamstring isometric strength improves immediately after performing RF static muscle stretching in young high-speed runners with RF shortening.

Keywords: Muscle stretching exercise, muscle strength, antagonist function, running, pelvic position.

Resumen

La lesión por sobrestiramiento de los isquiotibiales (HSI, por sus siglas en inglés) es la lesión más común en deportes que implican carreras de alta velocidad. La principal activación de los músculos isquiotibiales durante el esprint se produce principalmente en la fase final del balanceo, en la cual deben activarse contra la fuerza de los flexores de cadera. El objetivo de este estudio fue analizar si el estiramiento del músculo recto femoral (RF) produce un aumento inmediato en la fuerza y activación de los músculos isquiotibiales. Se llevó a cabo un ensayo clínico abierto y controlado, con un solo grupo, con mediciones pre y postratamiento. El estudio se realizó en el Centro Aragonés de Deportes y se reclutaron 16 corredores de alta velocidad (10 mujeres y seis hombres). Se registraron la longitud del recto femoral y la fuerza isométrica de los isquiotibiales como variables principales, mientras que la electromiografía de superficie (sEMG), la tensiomiografía (TMG) y la posición pélvica se consideraron variables secundarias. No se observaron diferencias en ninguna de las variables entre las mediciones basales y las de control. Se registró un aumento en la longitud del RF (p<.002) y en la fuerza isométrica de los isquiotibiales (p<.001) entre las mediciones basales y las posteriores al tratamiento, con un tamaño del efecto grande para ambas (0.88 y 0.81 respectivamente, medido con la prueba d de Cohen). Parece que la fuerza isométrica de los isquiotibiales mejora de forma inmediata tras realizar un estiramiento estático del RF en corredores jóvenes de alta velocidad con acortamiento del mismo.

Palabras clave: Ejercicio de estiramiento muscular, fuerza muscular, función del antagonista, carrera, posición pélvica.

Introduction

Hamstring strain injury (HSI) is the most common injury in sports including high-speed running (Tokutake et al., 2018) resulting in prolonged absence for athletes at all levels of competition (Erickson & Sherry, 2017; Sherry, 2012). It has been reported HSI to account for half of all muscular injuries in sprinters with an incidence varying from 10% to 24% depending on the follow-up time (Agre, 1985; Guex et al., 2012; Sugiura et al., 2008). Several studies have shown biceps femoris (BF) injury incidence is higher than medial hamstrings injuries (Chumanov et al., 2011; Thelen et al., 2005).

Regarding sprinting biomechanics, it has been described that the main activation of the hamstring muscles is in late swing phase (Chumanov et al., 2011; Chumanov et al., 2012). Hamstring concentrically extend the hip in order to swing the thigh backwards and eccentrically contract to decelerate the forward swinging of the lower leg which generates the highest hamstring electromyographic activity over the entire sprint acceleration (Mann, 1981; Morin et al., 2015; Sugiura et al., 2008). This has also been reinforced by evidence suggesting eccentric knee flexion strengthening along with hip extension strengthening as an efficient approach to improving sprint acceleration performance (Morin et al., 2015).

A multifactorial aetiology for the hamstring injuries has been proposed based on the biomechanics and morphology of these muscles. Functional studies have established a lower concentric hamstring to quadriceps strength ratio as a risk factor for HSI (Lee et al., 2018) and also that further hip flexion position may increase the length of hamstring thus reducing their maximum force potential (Kellis et al., 2019). Therefore, in high-speed running hip extensor moment seems to be present from midswing phase until early stance together with a knee flexor moment during the last swing phase, which implies that a considerable load is transmitted to the hamstring muscles (Schache et al., 2012). The maintenance of greater hip flexion angle has also shown to reduce hamstring force (Kellis et al., 2019) and that is why HSI prevention could target lengthening of hip flexors in order to allow better biomechanics of speed running.

The effect of muscle flexibility on pelvic position has been previously studied for the hip extensors where a decrease in hamstring length led to an increase in pelvic retroversion (Ferenczi et al., 2020). However, the effect of lack of flexibility of the hip flexors on pelvic position has not been analysed to date.

Stretching has traditionally had the potential to reduce injury risk (Safran et al., 1989), however preexercise static stretching has also shown to have a negative impact on strength and power performances in high-speed running regarding the agonist muscle or the performance of a functional task (Fletcher & Anness, 2007; Fletcher & Jones, 2004). To date, there is little evidence concerning to what happens to antagonist muscles after stretching (Miranda et al., 2015; Sandberg et al., 2012; Wakefield & Cottrell, 2015) but it seems it could improve performance measured by strength and activation variables.

Static stretching may contribute to muscle inhibition and reciprocally facilitate the increase in muscle activity and strength of the antagonists (Sandberg et al., 2012) and it appears that hip flexor tightness could limit hip extensor activation and strength. Therefore, the hypothesis of this study is that RF muscle stretching produces immediate effects in hamstring strength and activation and in pelvic position in sprinters.

Material and Methods

Study Design

An open-label, single-arm, control, pretest-posttest clinical trial was conducted in the Aragonese centre of Sports. The Clinical Research Ethics Committee of IDIAP Jordi Gol approved this study prior to subject enrolment and the study conformed to the Declaration of Helsinki. The study was registered at the US National Institutes of Health website: ClinicalTrials.gov (NCT04344691) and informed consent was obtained from each participant.

Participants

To be included the athletes had to be under regular training and competition with at least three days training weekly for the last three years and free of any symptoms. Participating subjects were instructed to avoid strength training or strenuous activities 24 hours before the study. Subjects who had suffered lower limb or back injuries during those last three years were excluded.

Sixteen sprinters with no present lower limb injuries were recruited into the study. The mean age was of 21.18 years (*SD* = 3.0). Of these, 62.5% were female (*n* = 10). The average height was 171.2 cm (*SD* = 6.5), and the mean body weight was 62.8 kg (*SD* = 7.5). Participants reported an average training volume of 9 hours per week (*SD* = 4.1). Most of the participants showed right leg dominance (81.3%, *n* = 13).

Measurements and Experimental Protocol

Testing was performed in a single session. Baseline measurements were registered for age, sex, leg dominance, height, weight and weekly training hours.

Dependent variables were registered at baseline, after 10 minutes control period and finally after RF stretching procedure. Dependent variables were knee flexion range of movement in RF stretching position, tensiomyographic (TMG) variables of RF, maximal isometric strength of hamstrings and gluteus maximus (GMax) measured by dynamometry and muscle activity of BF and GMax during sprinting measured by surface electromyography (sEMG). All measurements were performed in subjects' dominant leg which was determined according to the declaration of the subjects which leg they naturally use to kick a ball. The measurements were carried out by four different examiners experienced on the different protocols and one extra person registered the data, so the examiners were blinded to the results.

Pelvic Position

Pelvic tilt was registered by measuring photographs which were taken in a static lateral view of the subjects in normal standing position. A tripod was placed 1.5 metres away from the subject at the upper edge of the iliac crest height. The anterior tilt angle was calculated in each of the photographs based on an anatomical study measurement protocol (Preece et al., 2008). The reliability of this measuring protocol in this study gave an intra-tester reliability coefficient of .99 which is excellent.

Rectus Femoris Length Measurements and Stretching Technique

The technique consisted of a passive stretching performed by the physical therapist. Subject was lying prone and the leg to be stretched was placed on the treatment table while the other leg was supported on the floor outside the treatment table. The knee was flexed until firm resistance was felt, an inclinometer was placed distal to the ventral aspect of tibial tuberosity and knee flexion angle was measured (Figure 1.A).

Figure 1

Overview of Assessment Procedures and Measurement Setup

Note. A) RF stretching technique measurement; B) RF- tensiomyographic measurement; C) Hamstrings strength measurement; D) GMax strength measurement; E) sEMG electrode placement; F) sEMG sprint measurement.

For the stretching procedure, when firm resistance was felt three hold-relax cycles were performed until maximum resistance was achieved. At the point of maximum resistance, the technique was hold for 30 seconds (Hamberg et al., 1993; Tricás-Moreno et al., 2012).

Tensiomyography

The RF muscle was chosen in order to monitor if there was a change on the contractile parameters of the stretched muscle. It has frequently been used within previous TMG experimental studies (Calvo-Lobo et al., 2017; de Paula Simola et al., 2015; Wilson et al., 2018) and the large size of the muscle facilitates accurate palpation for TMG probe placement. The RF was stimulated using a TMG-S1 stimulator (TMG-BMC, Ljubljana, Slovenia) and radial muscle belly displacement was measured by a displacement transducer contained within a spring-loaded probe (GK40, Panoptik d.o.o., Ljubljana, Slovenia). Amplitude progressively increased from 20 to 100 mA by 20 mA increments until maximal response was obtained. Ten seconds of rest between the stimuli were allowed to minimize the effects of fatigue and potentiation (Shin et al., 2019). The contractile parameter of muscle displacement (Dm) variable was registered due to its relation with muscle tone (Pišot et al., 2008) and contraction time (Tc) was estimated from the displacement-time curve as the time between 10–90% of Dm (Wilson et al., 2018). Two self-adhesive electrodes (TMG-BMC, Ljubljana, Slovenia) were placed equidistant from the sensor, proximal (anode) and distal (cathode) to the sensor, with an inter-electrode distance of 5 cm (Figure 1.B).

Strength Testing Procedure

Muscle strength assessment was performed using a standardised protocol which remained the same for all the subjects. A handheld dynamometer (Lafayette Handheld dynamometer. Model 01165) was used for all strength measurements.

Hamstring

Subjects were sitting with the knee flexed 90° at the edge of the table. The handheld dynamometer was placed between subjects' heel and a firm support placed behind. Subjects were asked to perform maximal isometric knee flexion against the support for 5 seconds. This position was adapted from other protocols (Read et al., 2019; van der Made et al., 2021) in order to avoid gravity influence following similar procedures as for knee extensor strength measurements (Dolak et al., 2011) (Figure 1.C).

Gluteus Maximus

Subjects were placed in prone position for GMax strength testing with maximal hip joint extension and the knee flexed 90° (Lee & Oh, 2018; Yoshizawa et al., 2017). The handheld dynamometer was placed on the posterior thigh just proximal to the knee joint. Subjects were instructed to perform maximal isometric hip extension for five seconds (Figure 1.D).

Force Normalization

All strength measurements were registered three times, with one minute break between trials. Subject's hands were controlled in order to avoid compensatory movements. The peak force of each trial was recorded, and the average value was calculated.

Both hamstring and GMax strength were normalized using the following formula [(torque in Nm/body weight in N) x (subject height in metres x 100)] in which torque meant the peak force recorded by the dynamometer by the distance from lateral condyle to lateral malleolus for BF and from trochanter to lateral condyle for GMax (Dolak et al., 2011).

Sprinting sEMG

Surface myoelectrical activity at 1024Hz with a 250ms window with overlap of 50% of window size for BF and GMax was recorded by mDurance® system (mDurance Solutions SL, Granada, Spain). Surface electrodes were taped to the skin with respect to the underlying muscle fibre arrangement. They were located according to the Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles project (SENIAM) (Hermens et al., 2000). The electrodes were not taken out between measurements, so they were fixed in the same place in every measurement. The reference electrode was placed on the right patella (Figure 1.E). Low impedance of the skin electrode (<5 kΩ) was obtained by abrading the skin with emery paper and cleaning it with alcohol (Hermens et al., 2000; Morin et al., 2015). Muscle activity was recorded during 10m acceleration and normalized using first sprint as maximal record (Max) (van den Tillaar et al., 2017). The sEMG activity of each muscle was quantified using the root mean square (RMS) and maximal muscle activity during sprint. Both variables were expressed as a percentage of first sprint (Figure 1.F).

Statistical Analysis

The statistical analysis was carried out using the Statistical Package for the Social Sciences (SPSS) version 20.0. A one-way repeated measures analysis of variance (ANOVA) with *post-hoc* test using Bonferroni correction was used to analyse the differences among the three measurement moments. Statistical significance was set at $p<.05$. Descriptive statistics were obtained for all variables, and a correlation analysis was also carried out.

Sample size calculation was carried out based on previous studies using similar samples, variables and expected changes (Ruan et al., 2018; Serefoglu et al., 2017). The sample size was calculated for main dependent variables, estimating a two-tail test, a level of significance of.05, a power of.8 and no follow-up loss rate. The highest value obtained was 16 subjects.

The effect size was calculated to estimate the magnitude of the differences between baseline, control and post-treatment values with Cohen coefficients (d). Cohen coefficients were interpreted as follows: large effect sizes, $d> 0.8$; moderate effect sizes, $d = 0.5–0.79$; and small effect sizes, $d = 0.2–0.49$ (Cohen, 1988).

Results

Sixteen subjects were analysed, 10 women (62.5%) and six men (37.5%), 13 subjects had right leg dominance (81.3%) and three left leg dominance (18.8). Table 1 shows the demographic characteristics of the subjects.

Table 1

Baseline Characteristics of Participants

	Mean (SD)
Age (years)	21.18 (3.0)[a]
Female gender, n (%)	10 (62.5%)
Height (cm)	171.2 (6.5)[a]
Weight (Kg)	62.8 (7.5)[a]
Training hours (hours/week)	9 (4.1)[a]
Right leg dominance, n (%)	13 (81.3%)

Note. [a] Continuous variables are presented as mean (standard deviation); categorical variables are presented as n (%).

Baseline Data and Control Measurement

No significant differences were observed between baseline and control measurements (Table 2). The mean values and standard deviations for pelvic position, RF length, RF TMG variables, hamstring and GMax strength and BF and GMax sEMG variables as well as 95% confidence intervals are displayed in Table 2.

Table 2

Baseline Differences Between Pre-Treatment and Post-Treatment for Main and Secondary Outcomes

		Baseline	**Control**	**Difference From Baseline**		**Post-treatment**	**Difference From Baseline**		
		Mean ± *SD*	**Mean ± *SD***	***Mean* (95% *CI*)**	p^a	***Mean* ± *SD***	***Mean* (95% CI)**	p^b	***ES***
Main outcomes	RF length	121.43 ± 19.67	121.5 ± 19.39	0.625 (-2.59/2.72)	1.000	135.44 ± 11.11	14 (7.27/20.72)	<.002	.88
	HS strength	193.73 ± 46.11	203.59 ± 53.85	10.16 (-5.36/25.70)	<.547	236.31 ± 58.59	42.88 (23.93/61.84)	<.001	.81
Secondary outcomes	RF TMG-Tc	38.05 ± 8.73	41.19 ± 10.15	3.14 (0.47/5.81)	<.072	40.21 ± 8.29	2.15 (0.30/4.01)	<.077	--
	RF TMG-Dm	7.12 ± 0.63	6.80 ± 0.64	-0.31 (-1.10/0.47)	1.000	6.44 ± 0.55	-0.68 (-1.61/0.25)	<.419	--
	GMax strength	298.48 ± 86.12	300.31 ± 67.69	-1.94 (-47.35/43.46)	1.000	311.64 ± 75.44	9.38 (-38.18/56.96)	1.000	--
	sEMG-BF (%)	100 ± 0*	105.96 ± 71.91	5.96 (-32.36/44.28)	1.000	119.02 ± 79.67	19.02 (-23.44/61.47)	1.000	--
	sEMG-GMax (%)	100 ± 0*	127.36 ± 125.66	27.36 (-39.60/94.32)	1.000	89.09 ± 52.17	-10.91 (-38.70/16.90)	1.000	--
	Pelvic position	-13.2 ± 3.93	-11.86 ± 4.72	1.33 (-0.39/3.06)	<.359	-11.8 ± 4.16	1.4 (-0.50/3.30)	1.000	--

Note. *CI*, confidence interval, RF, rectus femoris; TMG, tensomyography; TC, contraction time; HS, hamstring; GMax, gluteus maximus; EMG, electromyography; BF, biceps femoris; ES, effect size.

[a] Comparison between baseline and pre-treatment. [b] Comparison between baseline and post-treatment.
*Baseline sprint was considered reference muscle activity

Post-Intervention Results

Significant ANOVA main effects were found for RF muscle length (*p*<.002) and hamstring strength (*p*<.001) when comparing baseline and post-intervention measurements. Those differences were not observed for GMax strength. Effect size was calculated for the variables which showed differences with Cohen's d-test and the effect was large both for RF length (0.88) and for hamstring strength (0.81).

No statistical differences were found for none of the TMG, sEMG or for pelvic position variables after the intervention (Table 2).

A correlation analyses was also carried out and no statistical correlations were found between pelvic position and hip extensors strength or between RF length and hip extensors strength although both showed a significant improvement at post-intervention.

Discussion

Regarding the main objective of the study the results showed a significant improvement in hamstring strength following RF static stretching technique. This finding contradicts previous similar studies´ results in which no performance change was found (Serefoglu et al., 2017). Even most of the studies in the current literature about muscle stretching have investigated the strength variability only in the stretched muscle, the results of this study add to the evidence in relation to the responses of the ipsilateral non-stretched antagonist muscles (Fletcher & Jones, 2004; Miranda et al., 2015; Sandberg et al., 2012). The different results obtained in this study could mainly be derived from the fact that the participants showed baseline RF muscle shortening regarding normative data (Witvrouw et al., 2003; Witvrouw et al., 2004) and no previous literature regarding the effects of stretching on the antagonist muscles has shown such results. Also, the differences could stem from methodological considerations such as strength measuring protocol and the type of stretching technique. Serefoglu et al. (2017) performed their study with very similar methodology; however, they did not focus on the effects of the stretched muscles, so it is not possible to compare their results regarding RF length.

In the results of the present study a statistically significant RF length improvement was obtained. It was hypothesized that this improvement could led to a change in pelvic position which could have resulted in a better mechanical activation of the hamstring muscles, however this could not be demonstrated since no significant correlations between agonist and antagonist muscle performance changes nor a significant change in pelvic position were observed. As antagonic co-activations are common in order to prevent overloading of the joints during sports activities (Serefoglu et al., 2017), it could be that the change produced in RF lead to a change in hamstring strength.

According to co-activation phenomenon, the antagonist muscles of the agonist, which cross the same joint, are coordinately activated during dynamic and functional movements in order to hold a position (Bazzucchi et al., 2006). In this study the strength of both hamstrings and GMax was analysed, however, only improvements for the hamstring muscles were observed. A reason for this could be that biarticular muscles such as RF and hamstrings have a more direct antagonism relationship in which their function in the knee joint is also antagonic and mechanically relevant for high-speed runners.

Non-significant sEMG activity changes were found in this study as it has happened in similar studies (Serefoglu et al., 2017) although unlike in those researches an improvement in isometric strength after the static stretching technique was observed. This difference could be because of the already mentioned fact of recruiting subjects with non-painful RF shortening in which the range of motion (ROM) improvement could have determined some of the other clinical results. Previous studies which investigated about muscle sEMG activity following stretching procedures of agonist muscles establish different hypothesis to explain the mechanisms by which static or dynamic stretching affects strength performance. Those studies conclude that sEMG activity seems to decrease as strength decreases after static stretching and it seems to increase as strength increases after dynamic stretching (Sekir et al., 2010). However, no hypotheses are known regarding the mechanisms concerning the antagonist muscles.

Previous studies suggest a loss in contractile properties of passively stretched muscles (Sekir et al., 2010). However, in the present study the TMG variables did not show statistically significant differences. This fact could mean that RF stretching technique managed to improve muscle length and hamstring strength without reducing the contractile capacity of RF.

Injury prevention programmes should seek to replicate the muscle-tendon demands during the main mechanisms of injury and in the case of HSI eccentric training seems to have apparent success for their function on the late swing phase (Chumanov et al., 2012). However, hamstring strength generation during the whole swing phase is performed against antagonist muscle activity which should also be targeted in prevention programmes. So, the results of this study could settle a good basis in order to implement RF stretching for HSI prevention along with hamstring eccentric training.

Limitations

All the previously mentioned results should be interpreted with caution due to the small sample size and further studies should be carried out with more participants.

In this study pelvic angle was only measured in static standing position and despite the small differences shown between the participants in the study, this position doesn´t seem to relate to hip flexor muscle flexibility or hip extensor strength.

Measurements were done immediately after the stretching technique and these results add to the current literature of immediate effects of muscle stretching implication in the antagonist muscle performance. However, to date, no literature has analysed if the effects shown are maintained in time or neither what happens to muscle strength if the stretching procedure is performed during several days.

Another important limitation of the present study is the absence of a control group. Although a baseline measurement of each participant was used for within-subject comparison, the inclusion of an independent control group would have strengthened the methodological design. Larger sample sizes should consider incorporating a control group to allow between-group comparisons and improve the external validity of the findings.

Further similar studies should incorporate pelvic position measurements during the whole swing phase which constitutes the functional open chain movement for speed-running (Alizadeh & Mattes, 2019). The inclusion of this measurement could give insight into whether pelvic mobility and position during the different phases is relevant for hip flexors and extensors function during sprinting. Also, prospective cohort studies would be interesting in order to analyse if RF muscle stretching prevents HSI in sprinters.

Conclusion

According to the results of this study, it is possible to state that RF muscle static stretching which produces muscle lengthening does result in an immediate increase of hamstring isometric strength but does not affect their sEMG activity or pelvic position in young sprinters under regular training with RF muscle shortening.

These findings may have relevant clinical implications for injury prevention; however, this effect may be limited to a specific subgroup of sprinters presenting with baseline RF shortening. In athletes without such muscular restrictions, similar benefits might not be observed, and therefore, individual muscle length assessments should be considered before applying this intervention broadly. Further research is needed to confirm whether this strategy is effective across diverse athletic populations and to explore its potential role within comprehensive injury prevention programmes.

Ethics Committee Statement

The Clinical Research Ethics Committee of IDIAP Jordi Gol approved this study prior to subject enrolment and the study conformed to the Declaration of Helsinki. The study was registered at the US National Institutes of Health website: ClinicalTrials.gov (NCT04344691) and informed consent was obtained from each participant.

Conflict of Interest

The authors report there are no competing interests to declare.

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Authors’ Contribution

ARDE, LL AP and CL conceived and designed the methodology of the study. PF, EB, and NL gave technical support for all the specific data collection aspects. ARDE, AP, LL, NL, PF and CL performed experimentation and data collection. ARDE, LL, CL and EB interpreted the results, drafted the manuscript and prepared tables and figures. AP, NL and PF edited and critically revised the manuscript and finally all the authors approved the final version. There was an equal contribution of ARDE and LL.

Data Availability Statement

Research data to this article can be found online at: https://doi.org/10.17632/ssm3v8t6k2.2

References

Agre, J. C. (1985). Hamstring injuries: proposed aetiological factors, prevention, and treatment. *Sports Medicine, 2*(1), 21–33. https://doi.org/10.2165/00007256-198502010-00003

Alizadeh, S., & Mattes, K. (2019). How anterior pelvic tilt affects the lower extremity kinematics during the late swing phase in soccer players while running: A time series analysis. *Human Movement Science, 66*, 459–466. https://doi.org/10.1016/j.humov.2019.06.001

Bazzucchi, I., Sbriccoli, P., Marzattinocci, G., & Felici, F. (2006). Coactivation of the elbow antagonist muscles is not affected by the speed of movement in isokinetic exercise. *Muscle and Nerve, 33*(2), 191–199. https://doi.org/10.1002/mus.20462

Calvo-Lobo, C., Diez-Vega, I., Martínez-Pascual, B., Fernández-Martínez, S., De La Cueva-Reguera, M., Garrosa-Martín, G., & Rodríguez-Sanz, D. (2017). Tensiomyography, sonoelastography, and mechanosensitivity differences between active, latent, and control low back myofascial trigger points. *Medicine, 96*(10), 1–7. https://doi.org/10.1097/MD.0000000000006287

Chumanov, E. S., Schache, A. G., Heiderscheit, B. C., & Thelen, D. G. (2012). Hamstrings are most susceptible to injury during the late swing phase of sprinting. *British Journal of Sports Medicine, 46*(2), 90. https://doi.org/10.1136/bjsports-2011-090176

Chumanov, E. S., Heiderscheit, B. C., Thelen, D. G. (2011). Hamstring musculotenon dynamics during stance and swing phases of high-speedrunning. *Medicine and Science in Sports and Exercise, 43*(3), 525–532. https://doi.org/10.1249/MSS.0b013e3181f23fe8

Cohen, J. (1988). *Statistical power analysis for the behavioral Sciences*. Routledge.

de Paula Simola, R. Á., Harms, N., Raeder, C., Kellmann, M., Meyer, T., Pfeiffer, M., & Ferrauti, A. (2015). Tensiomyography reliability and prediction of changes in muscle force following heavy eccentric strength exercise using muscle mechanical properties. *Sports Technology, 8*(1–2), 58–66. https://doi.org/10.1080/19346182.2015.1117475

Dolak, K. L., Silkman, C., Mckeon, J. M., Hosey, R. G., Lattermann, C., & Uhl, T. L. (2011). Hip strengthening prior to functional exercises reduces pain sooner than quadriceps strengthening in females with patellofemoral pain syndrome: A randomized clinical trial. *Journal of Orthopaedic and Sports Physical Therapy, 41*(8), 560–570. https://doi.org/10.2519/jospt.2011.3499

Erickson, L. N., & Sherry, M. A. (2017). Rehabilitation and return to sport after hamstring strain injury. *Journal of Sport and Health Science, 6*(3), 262–270. https://doi.org/10.1016/j.jshs.2017.04.001

Ferenczi, A., Moraux, A., Gall, F., Thevenon, A., & Wieczorek, V. (2020). Relationship Between Spinal-Pelvic Sagittal Balance and Pelvic-Femoral Injuries in Professional Soccer Players. *Orthopaedic Journal of Sports Medicine, 8*(1), 1–8. https://doi.org/10.1177/2325967119894962

Fletcher, I. M., & Anness, R. (2007). The acute effects of combined static and dynamic stretch protocols on fifty-meter sprint performance in track-and-field athletes. *Journal of Strength and Conditioning Research, 21*(3), 784–787. https://journals.lww.com/nsca-jscr/abstract/2007/08000/THE_ACUTE_EFFECTS_OF_COMBINED_STATIC_AND_DYNAMIC.22.aspx)at%C3%84%C2%B1fta

Fletcher, I. M., & Jones, B. (2004). The Effect of Different Warm-Up Stretch Protocols on 20 Meter Sprint Performance in Trained Rugby Union Players. *Journal of Strength and Conditioning Research, 18*(4), 885–888. https://journals.lww.com/nsca-jscr/abstract/2004/11000/THE_EFFECT_OF_DIFFERENT_WARM_UP_STRETCH_PROTOCOLS.35.aspx

Guex, K., Gojanovic, B., & Millet, G. P. (2012). Influence of hip-flexion angle on hamstrings isokinetic activity in sprinters. *Journal of Athletic Training, 47*(4), 390–395. https://doi.org/10.4085/1062-6050-47.4.04

Hamberg, J., Björklund, M., Nordgren, B., & Sahlstedt, B. (1993). Stretchability of the rectus femoris muscle: Investigation of validity and intratester reliability of two methods including x-ray analysis of pelvic tilt. *Archives of Physical Medicine and Rehabilitation, 74*(3), 263–270. https://doi.org/10.5555/uri:pii:000399939390135W

Hermens, H. J., Freriks, B., & Disselhorst-Klug, G. (2000). Development of recommendations for SEMG sensors and sensor placement procedures. *Journal of Electromyography and Kinesiology, 10*(5), 361–374. https://doi.org/10.1016/s1050-6411(00)00027-4

Kellis, E., Ellinoudis, A., & Kofotolis,N. (2019). Effect of Hip Flexion Angle on the Hamstring to Quadriceps Strength Ratio. *Sports, 7*(2), 43. https://doi.org/10.3390/sports7020043

Lee, D. K., & Oh, J. S. (2018). Relationship between hamstring length and gluteus maximus strength with and without normalization. *Journal of Physical Therapy Science, 30*(1), 116–118. https://doi.org/10.1589/jpts.30.116

Lee, J. W. Y., Mok, K. M., Chan, H. C. K., Yung, P. S. H., & Chan, K. M. (2018). Eccentric hamstring strength deficit and poor hamstring-to-quadriceps ratio are risk factors for hamstring strain injury in football: A prospective study of 146 professional players. *Journal of Science and Medicine in Sport, 21*(8), 789–793. https://doi.org/10.1016/j.jsams.2017.11.017

Mann R. V. (1981). A kinetic analysis of sprinting. *Medicine and Science in Sports and Exercise, 13*(5), 325–328. https://doi.org/10.1249/00005768-198105000-00010

Miranda, H., Maia, M. D. F., Paz, G. A., & Costa, P. B. (2015). Acute effects of antagonist static stretching in the inter-set rest period on repetition performance and muscle activation. *Research in Sports Medicine, 23*(1), 37–50. https://doi.org/10.1080/15438627.2014.975812

Morin, J. B., Gimenez, P., Edouard, P., Arnal, P., Jiménez-Reyes, P., Samozino, P., Brughelli, M., & Mendiguchia, J. (2015). Sprint Acceleration Mechanics: The Major Role of Hamstrings in Horizontal Force Production. *Frontiers in Physiology, 6*, 404. https://doi.org/10.3389/fphys.2015.00404

Pišot, R., Narici, M. V., Šimunič, B., De Boer, M., Seynnes, O., Jurdana, M., Biolo, G., & Mekjavič, I. B. (2008). Whole muscle contractile parameters and thickness loss during 35-day bed rest. *European Journal of Applied Physiology, 104*(2), 409–414. https://doi.org/10.1007/s00421-008-0698-6

Preece, S. J., Willan, P., Nester, C. J., Graham-Smith, P., Herrington, L., & Bowker, P. (2008). Variation in pelvic morphology may prevent the identification of anterior pelvic tilt. *Journal of Manual and Manipulative Therapy, 16*(2), 113–117. https://doi.org/10.1179/106698108790818459

Read, P. J., Turner, A. N., Clarke, R., Applebee, S., & Hughes, J. (2019). Knee angle affects posterior chain muscle activation during an isometric testused in soccer players. *Sports, 7*(1), 13. https://doi.org/10.3390/sports7010013

Ruan, M., Li, L., Chen, C., & Wu, X. (2018). Stretch could reduce hamstring injury risk during sprinting by right shifting the length-torque curve. *Journal of Strength and Conditioning Research, 32*(8), 2190–2198. https://doi.org/10.1519/JSC.0000000000002645

Safran, M. R., Seaber, A. V., & Garrett, W. E. (1989). Warm-Up and muscular injury prevention: An Update. *Sports Medicine, 8*(4), 239–249. https://doi.org/10.2165/00007256-198908040-00004

Sandberg, J. B., Wagner, D. R., Willardson, J. M., & Smith, G. A. (2012). Acute effects of antagonist stretching on jump height, torque, and electromyography of agonist musculature. *Journal of Strength and Conditioning Research, 26*(5), 1249–1256. https://doi.org/10.1519/JSC.0b013e31824f2399

Schache, A. G., Dorn, T. W., Blanch, P. D., Brown, N. A. T., & Pandy, M. G. (2012). Mechanics of the human hamstring muscles during sprinting. *Medicine and Science in Sports and Exercise, 44*(4), 647–658. https://doi.org/10.1249/MSS.0b013e318236a3d2

Sekir, U., Arabaci, R., Akova, B., & Kadagan, S. M. (2010). Acute effects of static and dynamic stretching on leg flexor and extensor isokinetic strength in elite women athletes. *Scandinavian Journal of Medicine and Science in Sports, 20*(2), 268–281. https://doi.org/10.1111/j.1600-0838.2009.00923.x

Serefoglu, A., Sekir, U., Gür, H., & Akova, B. (2017). Effects of static and dynamic stretching on the isokinetic peak torques and electromyographic activities of the antagonist muscles. *Journal of Sports Science and Medicine, 16*(1), 6–13. https://www.jssm.org/jssm-16-6.xml%3EFulltext#

Sherry, M. (2012). Evaluation and treatment of acute hamstring strains and related injuries. *Sports Health, 4*(2), 107–114. https://doi.org/10.1177/1941738111430197

Shin, S., Milosevic, M., Chung, C. M., & Lee, Y. (2019). Contractile properties of superficial skeletal muscle affect postural control in healthy young adults: A test of the rambling and trembling hypothesis. *PLoS ONE, 14*(10), 1–18. https://doi.org/10.1371/journal.pone.0223850

Sugiura, Y., Saito, T., Sakuraba, K., Sakuma, K., & Suzuki, E. (2008). Strength deficits identified with concentric action of the hip extensors and eccentric action of the hamstrings predispose to hamstring injury in elite sprinters. *Journal of Orthopaedic and Sports Physical Therapy, 38*(8), 457–464. https://doi.org/10.2519/jospt.2008.2575

Thelen, D. G., Chumanov, E. S., Hoerth, D. M., Best, T. M., Swanson, S. C., Li, L., Young, M., & Heiderscheit, B. C. (2005). Hamstring muscle kinematics during treadmill sprinting. *Medicine and Science in Sports and Exercise, 37*(1), 108–114. https://doi.org/10.1249/01.MSS.0000150078.79120.C8

Tokutake, G., Kuramochi, R., Murata, Y., Enoki, S., Koto, Y., & Shimizu, T. (2018). The Risk Factors of Hamstring Strain Injury Induced by High-Speed Running. *Journal of Sports Science & Medicine, 17*(4), 650–655. https://www.jssm.org/jssm-17-650.xml-abst#

Tricás-Moreno, J. M., Hidalgo, C., Lucha, O., & Evjenth, O., (2012). *Estiramiento y autoestiramiento muscular en Fisioterapia.* OMT España.

van den Tillaar, R., Solheim, J. A. B., & Bencke, J. (2017). Comparison of hamstring muscle activation during high-speed running and various hamstring strengthening exercises. *International Journal of Sports Physical Therapy, 12*(5), 718–727. https://pdfs.semanticscholar.org/d1ec/38be81e46b2d6882b69c3d25598a5707b3aa.pdf

van der Made, A. D., Paget, L. D. A., Altink, J. N., Reurink, G., Six, W. R., Tol, J. L., & Kerkhoffs, G. M. (2021). Assessment of isometric knee flexor strength using hand-held dynamometry in high-level rugby players is intertester reliable. *Clinical Journal of Sport Medicine: Official Journal of the Canadian Academy of Sport Medicine, 31*(5), e271–e276. https://doi.org/10.1097/JSM.0000000000000793

Wakefield, C. B., & Cottrell, G. T. (2015). Changes in hip flexor passive compliance do not account for improvement in vertical jump performance after hip flexor static stretching. *Journal of Strength and Conditioning Research, 29*(6), 1601–1608. https://doi.org/10.1519/JSC.0000000000000794

Wilson, H. V., Johnson, M. I., & Francis, P. (2018). Repeated stimulation, inter-stimulus interval and inter-electrode distance alters muscle contractile properties as measured by Tensiomyography. *PLoS ONE, 13*(2), 1–15. https://doi.org/10.1371/journal.pone.0191965

Witvrouw, E., Danneels, L., Asselman, P., D'Have, T., & Cambier, D. (2003). Muscle flexibility as a risk factor for developing muscle injuries in male professional soccer players: A prospective study. *American Journal of Sports Medicine, 31*(1), 41–46. https://doi.org/10.1177/03635465030310011801

Witvrouw, E., Danneels, L., Van Tiggelen, D., Willems, T. M., & Cambier, D. (2004). Open versus closed kinetic chain exercises in patellofemoral pain: a 5-year prospective randomized study: A 5-year prospective randomized study. *The American Journal of Sports Medicine, 32*(5), 1122–1130. https://doi.org/10.1177/0363546503262187

Yoshizawa, T., Higashi, K., & Katou, T. (2017). Measuring hip flexor and extensor strengths across various postures using a fixed belt. *Journal of Physical Therapy Science, 29*(4), 572–575. https://doi.org/10.1589/jpts.29.572