Influence of thigh muscularity on sprint mechanical properties and performance

Influència del desenvolupament muscular de la cuixa sobre les propietats mecàniques de l'esprint i el rendiment

Sergi Nuell Turon

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SERGI NUELL TURON · 2019

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Barcelona, 2019

INEFC Institut Nacional d'Educació Física de Catalunya
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Facultat d’Educació

INSTITUT NACIONAL D’EDUCACIÓ FÍSICA DE CATALUNYA

Centre de Barcelona

Programa de Doctorat

Activitat Física, Educació Física i Esport

Influence of thigh muscularity on sprint mechanical properties and performance

Influència del desenvolupament muscular de la cuixa sobre les propietats mecàniques de l’esprint i el rendiment

Tesi doctoral presentada per:

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Tutoritzada per:

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Per optar al títol de doctor per la Universitat de Barcelona

Barcelona 2019

A tu, mama, pel teu amor
i la teva dedicació incondicional cap a mi.

Aquesta tesi ha estat realitzada i finançada gràcies al suport de l'Institut Nacional d'Educació Física de Catalunya (INEFC) i del Grup de recerca en Activitat Física i Salut (GRAFIS, 2017SGR/741) dins del marc del projecte MICIN DEP2016-80085-R (AEI/FEDER, UE).

En Sergi Nuell Turon ha rebut el suport d'una beca predoctoral concedida dins del marc dels ajuts per la contractació de personal investigador novell de l'INEFC (PINEFC-2016).

This thesis is supported by the following papers:

Nuell S., Illera V., Carmona G., Macadam P., Lloret M., Padulles JM., Alomar X., Cadefau JA. ***Hamstrings muscle volume is associated with superior sprint performance in national-level sprinters compared to recreational trained subjects.*** (2018) Under review (IJSPP.2018-0848) International journal of sports physiology and performance.

Nuell S., Illera V., Carmona G., Alomar X., Padulles JM., Lloret M., Cadefau JA. ***Hypertrophic muscle changes and sprint performance enhancement during a sprint-based training macrocycle in national-level sprinters.*** (2019). European journal of sport science.
Accepted on fifth of September of 2019. Pending of DOI.

Nuell S., Illera V., Carmona G., Alomar X., Padulles JM., Lloret M., Cadefau JA. ***Sex differences in thigh muscle volumes, sprint performance and mechanical properties in national-level sprinters.*** (2019). Under review (PONE-D-19-15664) PLOS ONE.

This thesis is supported by the following conference presentations:

Nuell S., Illera V., Alomar X., Carmona G., Padullés JM., Padullés X., Conesa S., Lloret M., Cussó R., Cadefau JA. ***Relationship between strength, jump and velocity profile to sprint performance of sprinters during a follow-up of an indoor season.*** XXIII annual Congress of the European College of Sports Science, 2017. Metropolis Ruhr 2017 (Germany).

Nuell S., Illera V., Carmona G., Alomar X., Padullés JM., Lloret M., Cussó R., Cadefau JA. ***Changes in muscle volume, sprint mechanical properties and performance in sprinters during an indoor track and field macrocycle.*** XXIII annual Congress of the European College of Sports Science, July 2018. Dublin (Ireland).

Nuell S., Illera V., Carmona G., Alomar X., Padullés JM., Lloret M., Cussó R., Cadefau JA. ***Diferències en volums musculars i rendiment en l’esprint entre velocistes d’alt nivell i joves esportistes.*** II Jornada Catalana de Recerca, Octubre 2018. Barcelona (Espanya).

Agraïments

Al finalitzar un treball d’aquesta magnitud, amb l’esforç i dedicació que suposa, és fàcil que l’ego ens porti a pensar que el mèrit és d’un mateix. No obstant, la consecució amb èxit d’una tesi doctoral implica l’esforç de moltes persones, especialment per algú tant eixelebrat com jo. Per tant, vull dedicar les pròximes línies a totes les persones que han fet possible aquest moment.

A la meva mare, per tots els esforços que vas fer per donar-me la millor vida que podia tenir. Tot i el que et va tocar viure, res ni ningú et va prendre el somriure ni les ganes de seguir endavant: sempre seràs el meu referent. Mama, ets la millor persona que he conegut mai, aquest treball va especialment dedicat a tu.

Cristina, gràcies per haver-me encoratjat en aquesta aventura i haver estat al meu costat durant tot el procés. Sense el teu amor i el teu suport res d’això hauria estat possible.

Als meus directors de tesi, en Joan Cadefau i en Gerard Carmona.
Joan, gràcies per haver confiat en mi per a aquest projecte, per la teva paciència, pel teu coneixement científic i per haver-me aplanat el camí quan es complicava. Als inicis de la meva etapa formativa em vas obrir les portes de la recerca i acabar aquesta etapa amb tu és la millor manera d’agrair-t’ho. Però, sobretot, et vull donar les gràcies pel teu optimisme i sentit de l’humor, i per la teva amistat.
Gerard, gràcies per haver estat sempre disponible, per haver-me ajudat al llarg de tot el procés i per haver compartit el teu saber fer científic i no científic amb mi. La teva aportació en aquest treball és incalculable. Et vaig conèixer durant les primeres etapes de la meva formació i de seguida et vas convertir en un referent professional per a mi; que m’hagis acompanyat en aquest procés té un valor infinit per a mi.

A l’Helga i la Mònica, per ser les millors germanes que podia tenir. La meva gratitud i amor cap a vosaltres s’estén molt més enllà d’aquestes paraules. La família no es tria, però si en una altra vida tingués l’oportunitat de triar-la, sense cap dubte tornaríeu a ser les meves germanes.

A en Miquel, per ser la figura paterna que necessitava, per haver estat sempre al lloc i al moment adequat. M'has ensenyat molt, no t'estaré mai prou agraït.
A en Marc i la Laura, per ser els germans petits que mai vaig tenir. Vosaltres també heu fet que sigui qui soc avui.
A en Ricard, per haver-me cuidat sempre com un fill i per fer sempre les coses fàcils. Gràcies per la teva paciència i dedicació a mi.

A en Víctor, en Bruno i en Josep, els meus companys de viatge, per tot el que m'heu ensenyat, totes les vivències i tot el que hem compartit durant aquesta etapa. Això tot just acaba de començar!

Vull fer palesa la meva gratitud a la institució que m'ha vist créixer, l'Institut Nacional d'Educació Física de Barcelona, i a tots els seus treballadors que han col·laborat d'una manera o altra en el desenvolupament d'aquest projecte.
A la Maribel Pérez, pel *carinyo* amb què m'ha tractat durant tot el procés i per haver-me guiat dins el laberint burocràtic inherent a la tesi.
A la Carme Suárez, pels incomptables favors i ajudes durant aquest viatge, i sobretot per haver-ho fet sempre amb un somriure.
A en Josep Sòria, per haver-me ajudat a neutralitzar la meva *kriptonita*, la informàtica.

I would like to thank John Cronin for opening the New Zealand and SPRINZ doors to me, and for making me feel like one of his team throughout all the time. John you are a really good man; I hope our paths will cross again.
I would also like to thank all my colleagues and friends from SPRINZ for having me in their home, and for the time, the experiences and the research we shared.

A en Blai Ferrer, per tots els moments compartits, per les incomptables ajudes i per ser l'autèntic espartà. Ets un crack Blai, gràcies.

A en Padu, per tot el que has aportat al món de l'entrenament, per tot el que m'has ensenyat i sobretot per la teva amistat.

A en Xavier Alomar, per la seva col·laboració i esforços en aquest projecte i pel seu altruisme científic.

A en Sebastián Conesa, per la seva col·laboració desinteressada en aquest projecte i per l’interès que té en ajudar a evolucionar les ciències de l’entrenament.

A tots els esportistes (i els no tan esportistes) que he tingut ocasió d’entrenar i/o testar durant la meva vida, ja que gràcies a vosaltres he crescut com a preparador físic i investigador.

Per últim, i no menys important, vull donar les gràcies a tots i cada un dels voluntaris que han participat en els diferents estudis d’aquesta tesi; per la seva implicació, motivació i perquè sense ells aquest treball no hauria estat possible.

Abstract

Sprint performance is one of the most highly prized faculties in the vast majority of sports, from short accelerations seen in team sports to high maximal speeds reached in track and field events. The capacity to accelerate rapidly and to reach very high speeds is an extremely desirable quality across the sports world. Although many factors influence sprint performance, the ability to produce high horizontal ground reaction forces (GRFs) throughout the sprint seems the ultimate determinant. This ability is inclusive of mechanical properties of the muscles, morphological features and neural mechanisms as well as the ability of the given athlete to orient horizontal GRFs. Moreover, it is known that muscle volume (MV) is closely related to the ability to produce force and power in any given muscle, therefore, it is logical to suppose that larger muscles would be advantageous for sprint performance. However, enlargement of a muscle increases inertia in the segment and reduces angular acceleration and velocity, which is counterproductive for the goal of improving sprint performance. Thus, the aim of this thesis was to analyse the influence of thigh muscularity (quadriceps, hamstrings and adductors) on sprint performance by examining different populations with different levels of sprint performance and to study the adaptation of these muscles during sprint-training periods in national-level sprinters.

In the first study (Study I), we analysed and compared thigh MVs, sprint performance and sprint mechanical properties (SMPs) from recreationally trained young men and male sprinters. Results from this study showed that sprinters accelerated better than trained males (ES = 2.12-3.68, $P < 0.01$), but more importantly, they were much faster at high speeds (ES = 4.53, $P < 0.01$). Sprinters also had larger thigh muscle volumes (ES = 1.12-2.11, $P < 0.01$), especially in the hamstring musculature. Moreover, strong correlations were found between hamstrings MV and sprint performance (r = -0.670, $P < 0.01$), and moderate correlations between adductors MV and sprint performance (r = -0.563, $P < 0.05$). Based on differences in thigh muscularity between these groups and the

correlations found, we concluded that hamstrings muscularity plays an important role in sprint performance.

Through the second study (Study II) we compared thigh muscularity, SMPs and performance between sprinters of both sexes. The analysis revealed that only normalised hamstrings MV differed between the sexes, being larger in males (ES = 1.26, $P < 0.05$), while quadriceps and adductors showed no differences. Males were much faster than females (ES = 5.01-6.68, $P < 0.001$) and exhibited greater SMPs (ES = 1.98-6.97, $P < 0.01$), especially at maximal velocity. As in Study I, strong correlations were found between hamstrings MV and sprint performance ($r = -0.685$, $P < 0.01$), and moderate between adductors MV and performance ($r = -0.530$, $P < 0.05$). Moreover, hamstrings muscularity was related to maximal velocity and not to maximal horizontal force, while adductors muscularity showed the opposite correlations. We concluded that hamstrings muscularity is more important than adductors muscularity in determining performance in sprinting. Moreover, hamstrings MV seems more important for reaching very high speeds than adductors MV.

Finally, in the third study (Study III) we examined the effect of a 5-month sprint-based training macrocycle (SBTM) on sprint performance, thigh MVs and SMPs of national-level sprinters. The athletes were tested before, during and after the SBTM. Sprinters improved their sprint performance in all distances analysed (ES = 0.46-1.11, $P < 0.01$) as well as improving maximal velocity (ES = 0.40, $P < 0.01$) and the ability to produce horizontal GRFs throughout the sprint (ES = 0.91, $P < 0.01$). Moreover, we observed a highly consistent hypertrophic pattern in quadriceps, hamstrings and adductors, with increases during the first half of the period of training and maintenance during the second half. Hamstrings and adductors increases were almost the same, and double that of quadriceps. The greater increase in hamstrings and adductors might be related to the prominent role of these muscle groups during sprinting.

Resum

La capacitat d'esprintar és una de les qualitats més apreciades en la majoria d'esports, des de les curtes acceleracions típiques d'esports col·lectius a les extremes velocitats màximes de curses de velocitat de l'atletisme. La capacitat d'accelerar ràpidament i aconseguir velocitats molt altes sempre és una qualitat molt desitjada dins el món de l'esport. Tot i que molts factors influencien el rendiment en l'esprint, sembla que la capacitat de produir grans forces horitzontals durant l'esprint és el determinant més important. Aquesta capacitat inclou propietats mecàniques dels músculs, factors d'arquitectura i morfologia muscular, propietats del sistema nerviós, com també l'habilitat de l'atleta per orientar endavant aquestes forces. D'altra banda, és sabut que el volum muscular (MV) està estretament lligat a la capacitat de produir força i potència d'un múscul, llavors, sembla lògic pensar que músculs més grossos suposaran un avantatge per al rendiment en l'esprint. Malgrat això, l'engrandiment d'un múscul implica un augment del seu moment d'inèrcia, i així mateix, una reducció de l'acceleració i velocitat angular del segment, la qual cosa és contraproduent per al bon rendiment en l'esprint. Així, l'objectiu de la tesi va ser analitzar la influència del desenvolupament dels grups musculars de la cuixa (quàdriceps, isquiosurals i adductors) sobre el rendiment en esprint, analitzant diferents poblacions amb diferent nivell de rendiment, així com estudiar l'adaptació d'aquests grups musculars a un període d'entrenament d'esprint en velocistes de nivell nacional.

En el primer estudi (Estudi I), vam analitzar i comparar els MVs de la cuixa, les propietats mecàniques de l'esprint (SMPs) i el rendiment en un grup d'homes joves actius i entrenats i un grup d'homes velocistes. Els resultats d'aquest estudi van mostrar que els velocistes acceleraven molt millor que els actius (ES = 2,12-3,68; *P* < 0,01), però, sobretot, van ser molt més ràpids a velocitats altes (ES = 4,53; *P* < 0,01). Els velocistes també van mostrar tenir els músculs de la cuixa més grossos que els actius (ES = 1,12-2,11; *P* < 0,01), especialment els isquiosurals. A més, es van trobar fortes correlacions entre l'MV dels isquiosurals i el rendiment (r = -0,670; *P* < 0,01) i moderades entre l'MV dels adductors i el

rendiment (r = -0,530; *P* < 0,05). Basant-nos en les diferències entre MVs entre grups, es va concloure que l'MV dels isquiosurals juga un paper important en el rendiment en l'esprint.

En el segon estudi (Estudi II) vam comparar MVs de la cuixa, SMPs i rendiment entre velocistes de diferents sexes. Els resultats revelaren que només l'MV dels isquiosurals diferia entre sexes, essent més gran en els homes (ES = 1,26; *P* < 0,05), mentre que el de quàdriceps i adductors no presentaven diferències. Els homes van ser molt més ràpids que les dones (ES = 5,01-6,68; *P* < 0,001) i mostraren SPMs molt superiors (ES = 1,98-6,97; *P* < 0,01), especialment la velocitat màxima. Igual que en el primer estudi, es van trobar fortes correlacions entre l'MV dels isquiosurals i el rendiment (r = -0,685; *P* < 0,01) i moderades entre l'MV dels adductors i el rendiment (r = -0,530; *P* < 0,05). A més, l'MV dels isquiosurals va correlacionar amb la velocitat màxima i no ho va fer amb la força màxima horitzontal, mentre que l'MV dels adductors va mostrar correlacions oposades. Després de tot, vam concloure que el desenvolupament muscular dels isquiosurals sembla més important que el dels adductors de cara al rendiment en l'esprint. A més, l'MV dels isquiosurals sembla més important que el dels adductors per aconseguir velocitats molt altes.

Finalment, en el tercer i últim estudi (Estudi III) vam analitzar l'efecte d'un període d'entrenament específic d'esprint (SBTM) de 5 mesos sobre el rendiment, els MVs de la cuixa i les SMPs en velocistes de nivell nacional. Els atletes van ser sotmesos a tests abans, durant i després de l'SBTM. Els resultats mostren que els velocistes van millorar el rendiment en totes les distàncies analitzades (ES = 0,46-1,11; *P* < 0,01), juntament amb una millora de la velocitat màxima (ES = 0,40; *P* < 0,01) i un increment de la producció de forces horitzontals durant l'esprint (ES = 0,91; *P* < 0,01). A més vam observar un patró hipertròfic molt consistent en quàdriceps, isquiosurals i adductors, amb increments en l'MV durant la primera meitat del període i manteniment durant la segona meitat. També vam veure que l'augment en l'MV d'isquiosurals i adductors va ser pràcticament igual, i fou el doble que el dels quàdriceps. Aquest increment tan gran en isquiosurals i adductors, comparat amb els quàdriceps, podria estar relacionat amb el rol que tenen aquests grups musculars en el rendiment en l’esprint.

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Abbreviations

ATP	Adenosine triphosphate
BFlh	Biceps femoris long head
BFsh	Biceps femoris short head
CI	Confidence interval
CM	Centre of mass
CSA	Cross-sectional area
D_{RF}	Index of force application technique
DXA	Dual-energy x-ray absorptiometry
ES	Effect size
F_0	Theoretical maximal anteroposterior force
F-V	Force-velocity
GRF	Ground reaction force
IAAF	International Amateur Athletic Federation
IN	In-training tests (study III)
MRI	Magnetic resonance imaging
MV	Muscle volume
P_1	First period of training (study III)
P_2	Second period of training (study III)
P-F-V	Power-force-velocity
P_{max}	Maximal power output
POST	Post-training tests (study III)
PRE	Pre-training test (study III)
P-V	Power-velocity
RF	Rectus femoris
R_oF	Ratio of forces
SBTM	Sprint-based training macrocycle
SD	Standard deviation

SM	Semimembranosus
SMPs	Sprint mechanical properties
ST	Semitendinosus
V_0	Theoretical maximal velocity
VI	Vastus intermedius
VL	Vastus lateralis
VLI	Vastus lateralis + vastus intermedius
VM	Vastus medialis

1 INTRODUCTION

1.1 Sprint running

Sprint running is a fundamental motor task and an important component of many sports. In team sports, acceleration capacity is crucial for performance due to the shorter and multidirectional movements. In contrast, in track and field events, with longer distances, performance is mainly determined by acceleration capacity, maximum speed and maintenance of maximum speed. Performance in sprint running is generally measured by the time taken to cover a certain distance, or the distance covered in a certain time. The 100 m event is the standard measure of the most extreme speed capabilities of human bipedal locomotion and determines the ‘‘world’s fastest human’’ for a given period of time. More generally, it represents an assessment of the limits of human capabilities in sprinting, thereby providing an excellent basis for scientists to improve our insights into physiological, neural, and mechanical features.[1] In this field, elite sprinters represent a unique and precious sample to analyse for better understanding of sprint performance determinants and adaptations.

Sprint running is a movement pattern in which the body of the runner is propelled forward by forces exerted by the lower limbs. The mechanics of running require both feet to be off the ground at some point during the stride, whereas the mechanics of walking require at least one foot to be touching the ground at all times. Thus, during running there is a stance phase (one foot is in contact with the ground) and an aerial phase (both feet are in the air).[2,3] Sprint gait cycle is defined by the behaviour of just one leg, starting when it touches the ground and completing when the same leg touches the ground again. Therefore, sprint gait cycle can be divided into a stance phase (the foot of the leg being analysed is in contact with the ground) and a swing phase (the foot of the same leg is in the air).[2] The stance phase begins with the foot touchdown and ends at the toe off. The stance phase can be subdivided into the braking phase (the first half of the stance period), and the propulsion phase (second half).[2–4] During the swing phase the leg is driven forward and repositioned in preparation for the subsequent stance phase. The swing phase is generally subdivided into three phases: the early swing phase, the mid swing phase and the late swing phase (Figure 1.1).[2,3,5]

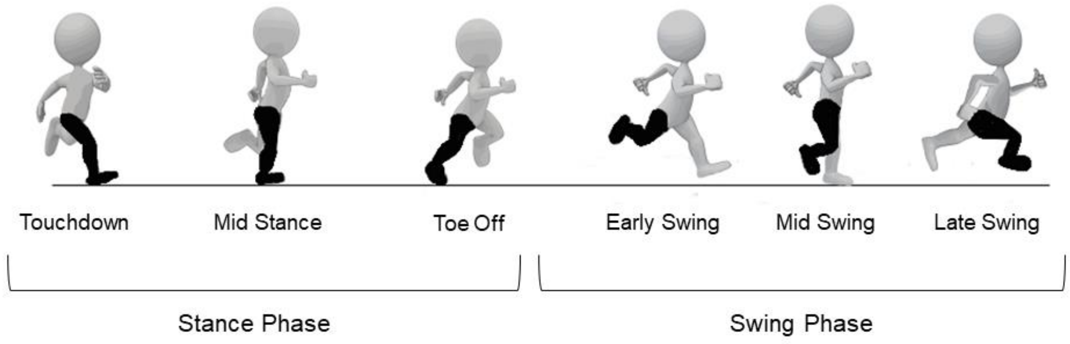

Figure 1.1 Sprint gait cycle.

Key phases of the sprint gait cycle. The sprint gait cycle starts with the touchdown of one foot and continues until the same foot touches the floor again. (Adapted from Howard et al.[6]*).*

Research in adults has shown the importance of the kinetic [i.e., horizontal and vertical ground reaction force (GRF)] and kinematic (i.e., step frequency, step length, contact time) parameters that comprise sprint running performance[2,4,7–9] and the differences in these variables between fast and slow athletes.[7,8,10,11] Development of sprint running performance is linked to differences in factors such as height, muscle mass or additional development of strength and power.[7,12,13] Improvements in strength and power seem to influence sprint running performance through step length, while improvements in step frequency are attributed to neuronal factors.[14,15]

The GRF is an external force provided by the supporting surface that the athlete is in contact with, and represents the reaction of the support surface to the actions of the athlete.[5] The resultant GRF can be resolved into three orthogonal components: anteroposterior, mediolateral and vertical. These three components act to accelerate the centre of mass (CM) of the athlete only during the stance phase of every sprint stride.[5] It has been shown that the vertical and anteroposterior (also referred by horizontal) components of GRFs are the main determinants of the running motion and CM displacement in the sagittal plane. [5,16] During the sprint, from standing still until maximum velocity is reached, the magnitude of the horizontal GRFs decreases as the athlete traverses the acceleration phase and attains maximal speed, whereas the vertical GRFs increase concomitantly (Figure 1.2). These changes in the magnitude of the two components are associated with; the greater requirement for horizontal acceleration of the CM during the acceleration phase,[8,16] and the requirement to support body weight and project the CM into an aerial phase of sufficient duration to reposition the swing leg when sprinting at maximal speed.[5,17] Weyand et al.[7,17] related the specific ability to run at maximum speed to the production of high amounts of vertical GRF per unit of body weight and the time taken to apply these high amounts of force onto the supporting ground. They noticed that faster sprinters were able to apply more force onto the ground in less time than slower sprinters. However, the conclusions of Weyand et al.[7,17] came from studies using a treadmill at constant speeds, which does not reproduce what actually happens in practice on the field or track, where the acceleration phase is intrinsic to the sprint. In this regard, recent literature supports the notion that the anteroposterior GRFs, or the ability to produce propulsive forces throughout the sprint is the major determinant of acceleration and sprint performance.[1,8,10,11,18] In fact, Hunter et al.[4] suggested that all the force should be applied forward, with the exception of a magnitude of relative vertical forces that enable sufficient flight time to reposition the lower limbs as fast as possible. Moreover, work from Morin et al.[8,11,16] showed that the magnitude of the horizontal component of the GRF per unit of body weight is the strongest predictor of sprint performance, rather than the vertical GRF or total GRF. Additionally, Rabita et al.[18] showed that elite sprinters produced higher horizontal GRFs, but showed no difference in the resultant GRF compared to sub-elite sprinters.

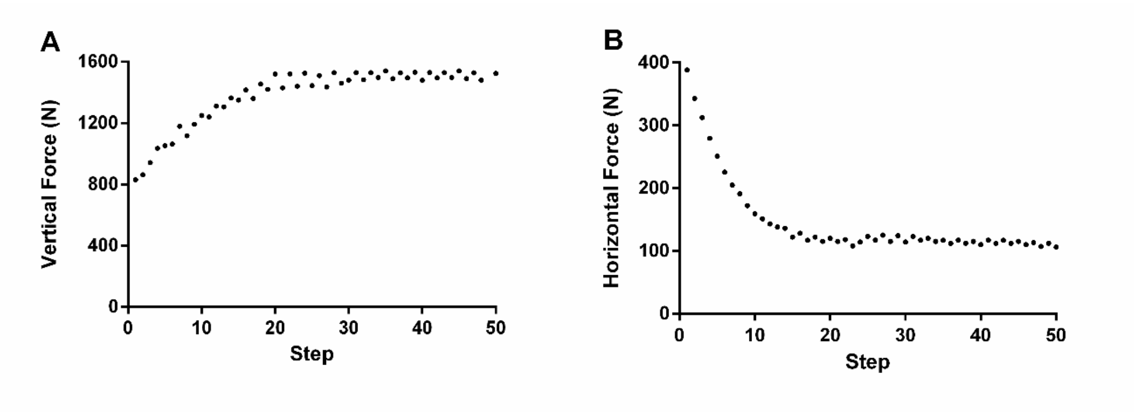

Figure 1.2 Vertical and horizontal GRFs during sprinting.

The averaged vertical (A) and horizontal (B) forces applied during each stance phase during a 100 m sprint. (Unpublished data from our research group).

Running speed is attained through the combination of step frequency and step length.[5,19] While longer step length, higher step frequency or the combination of both, theoretically, lead to improvements in sprinting speed, there is a negative relationship between step length and step frequency.[9,19] Although step frequency remains fairly constant through the acceleration until maximum speed is reached, step length increases progressively until maximum speed is attained.[9,18,20] Research into maximal sprint running has been inconclusive in identifying which is the most important contributory factor in performance: step length or step frequency.[5,9,14,19] Moreover, one of the factors determining the combination of step length and step frequency is the GRF.[9,19] Greater vertical GRFs during the accelerated sprint lead to longer step length and lower step frequency and vice versa.[19]

1.1.1 Force-velocity profile in sprinting

The ability of skeletal muscle to generate force and the maximal rate of movement are described in the force-velocity (F-V) relationship. The relationship postulates that for a given constant level of muscle activation, increasing muscle-shortening velocity decreases force production by the neuromuscular system.[21,22] Although these relationships are described by a hyperbolic equation when obtained in isolated muscles, linear relationships have been consistently obtained for functional multi-joint movements.[18,21–23] Therefore, the overall mechanical capabilities needed to produce anteroposterior GRFs during sprint running are well described by the inverse linear F-V and the parabolic power-velocity (P-V) relationships (Figure 1.3).[18,24,25] These relationships characterise the mechanical limits of the entire neuromuscular system to produce anteroposterior force when increasing running velocity, and are well summarised through the theoretical maximal force at null velocity (F_0), the theoretical maximal velocity when force equals zero (V_0) and the associated maximal power output (P_{max}). F_0 and V_0 represent the *y* and *x* axes intercepts of the linear regressions, respectively. P_{max} corresponds to the apex of the parabolic P-V relationships.[24,25] They encompass individual muscle mechanical properties, morphological factors, neural mechanisms and segmental dynamics; commonly known as sprint mechanical properties (SMPs).

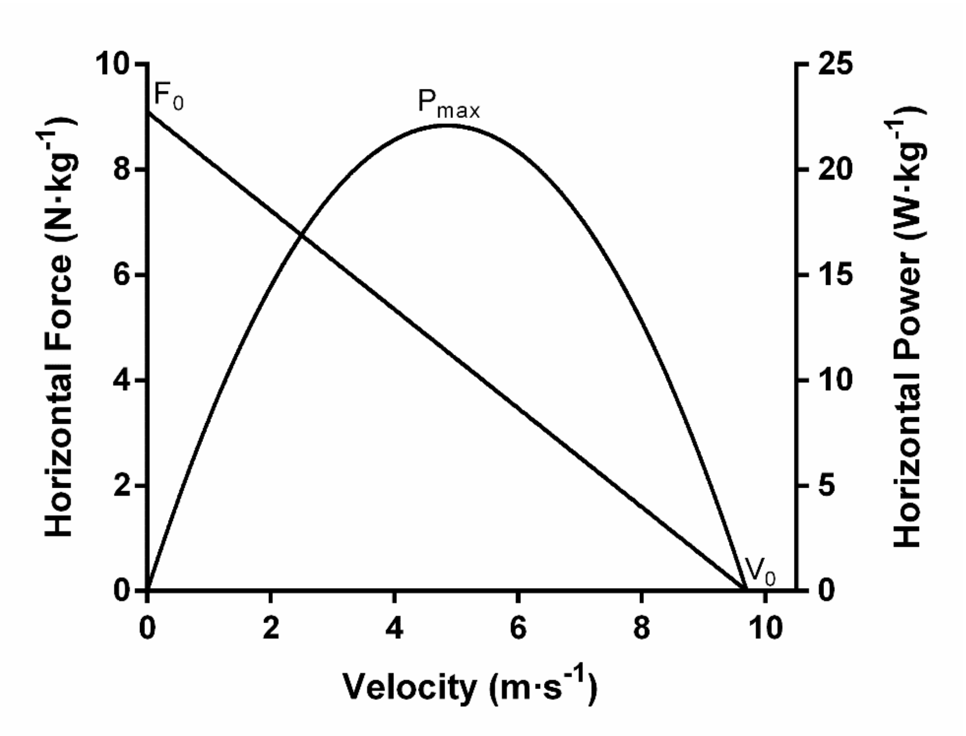

Figure 1.3 Sprint power-force-velocity profile.

Graphical representation of the relationship between force-velocity and power-velocity profiled during an accelerated sprint, representative of sprint mechanical properties. F_0*, theoretical maximal horizontal force.* V_0*, theoretical maximal horizontal velocity.* P_{max}*, maximal horizontal power. (Unpublished data from our research group).*

The SMPs integrate the technical ability of a given athlete to apply the external force effectively onto the ground. This concept of mechanical effectiveness of force application during sprinting has been quantified at each step by the ratio of forces (R_oF) and it represents the ratio of net anteroposterior GRF to the corresponding total GRF (Figure 1.4).[8,24] During acceleration, only the anteroposterior component of GRF is directed forward, however, due to the gravitational constraints, the vertical component of GRF is ineffective but totally necessary to move forward. The linear decrease in R_oF as velocity increases is described as an index of force application technique (D_{RF}). D_{RF} is independent from the amount of total force (i.e., physical capabilities) and represents the ability to apply horizontal force as running speed increases.[8,24,25] Moreover, D_{RF} has been proposed as one of the main determinants of 100 m performance and also, as one of the differential factors between sprint specialists and recreational athletes.[8,11,18] Thus, F-V and P-V relationships provide a macroscopic and integrative view of the P-F-V mechanical profile in the specific sprint running task.[24]

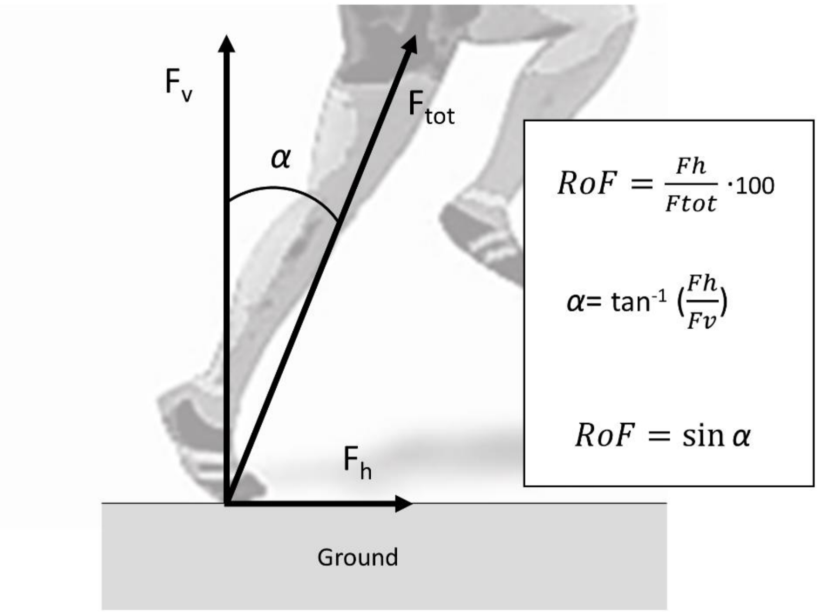

Figure 1.4 Graphical representation of the ratio of forces.

Decomposition of horizontal and vertical forces from the total force in the sagittal plane during a ground contact phase. Note that R_oF *represents the percentage of the total force directed forward and is represented by the angle* α*.* R_oF*, ratio of forces.* F_v*, vertical ground reaction force.* F_h*, horizontal ground reaction force.* F_{tot}*, resultant ground reaction force. (Adapted from Morin et al.*[8]*).*

1.2 Muscle adaptations to sprint training

It is known that resistance training induces profound and specific changes in muscle composition, size and morphology[26,27] and is probably the fastest way to produce to these changes. Less is known about exercise-induced muscle changes in sprint training, however the adaptations of muscle to sprint training can be separated into metabolic and morphological changes.[28]

During short-term bouts of maximal intensity exercise, high-energy phosphagens, glycolysis and oxidative metabolism all contribute to adenosine triphosphate (ATP) turnover. Enzyme adaptations represent a major metabolic feature of sprint training, with the enzymes of all three energy systems showing signs of adaptation to training.[28,29] Morphological adaptations to sprint training include changes in muscle fibre type, sarcoplasmic reticulum and fibre cross-sectional area (CSA). Even though these adaptations take place at a microscopic level, they have the potential to induce whole-muscle-size changes.[27]

Sprint training has the potential to induce changes in fibre type.[28–30] Skeletal muscle fibres are broadly classified as “slow-twitch” or type I and “fast-twitch” or type II, and at the same time the “fast-twitch” fibres are classified as type IIa (intermediate) and type IIx (purely fast).[31] Despite a lack of full agreement in the literature, a shift towards IIa fibre type (I→IIa←IIx) could be expected after proper sprint training.[30,32] Duration of the sprint and rest between bouts would affect these adaptations, but a shift towards fibre type IIx (I→IIa→IIx) is rarely seen after sprint training.[28] In contrast, this adaptation has been seen after 3 months of rest/detraining.[33] When long sprint distances, short rests and high training frequency are undertaken during sprint training, a shift towards fibre type I (I←IIa←IIx) is noticed,[29] indicating that the sprint training protocol has not been appropriate.[28] Type IIa fibres are more fatigue resistant than type IIx, but still explosive, and may be a more suitable adaptation for the sprint athlete, playing a role in determining sprint performance.[28] It is well know that type II fibres are more susceptible to hypertrophy and atrophy than type I,[31] therefore changes in muscle size, measured at a macroscopic level, after sprint training are easily attributable to shifts towards fibre type II.

Very few studies have analysed the hypertrophic effects of sprint training. In a review of muscle adaptations to short sprint training, Ross et al.[28] reported increases in fibre CSA from 5 to 12% after sprint training ranging in duration from 6 to 14 weeks. Additionally, Cadefau et al.[29] found between 8 to 16% increase in fibre diameter after 8 months of sprint training in young athletes. In contrast, Allemeier et al.[34] did not find any change in CSA after 6 weeks of sprint training. Thereafter, it seems there is a lack of investigation into sprint training and muscle size changes.

1.2.1 Muscularity and sprint performance

Skeletal muscle is the most abundant tissue in the human body and it is essential for the movement. Although many factors may influence the sprint performance, force production seems to be one of the most important,[35,36] and it is generally accepted that a close relationship exists between muscle CSA and its ability to generate force.[37,38] However, to move the body forward during sprinting, humans have to produce large lower limb joint torques and muscle volume (MV) has been identified as the main determinant of joint torque in humans.[37,39] Therefore, it seems critical to explore which volumes of lower limb muscles are important for achieving fast running speeds.

Athletes participating in different sports differ in physique. Particular characteristics of body build and composition tend not only to typify proficient performers of specific athletic activities, but they may also, in some instances, distinguish between performers of different levels of proficiency in the same event.[40,41] When comparing sprinters to the average population, the differences in muscularity are noticeable.[42,43] Furthermore, some studies have provided evidence that, compared with their nonathletic peers, athletes show a prominent development in muscle groups primarily used in their competitive activities and/or training regimens.[41,44,45] Since larger muscles will produce greater force and power,[37,42,43] it might be expected that extremely large muscles are advantageous for sprint performance. However, we should be cautious with this supposition since enlargement of a muscle increases the moment of inertia of the segment and hence, reduces the limb's angular acceleration for a given joint torque.[42,46]

So far, studies investigating the relationship between lower limb muscularity and sprint performance have produced some controversy in the results.[46–50] Some authors found positive relationships between quadriceps muscularity and performance in sprint.[49,51,52] Nevertheless, Miyake et al.[50] observed that the knee extensor moment arm, and not quadriceps CSA, was correlated with sprint performance. Size of the adductor muscle group has also been identified as a determinant of sprint, showing positive correlations with performance.[48,49] Likewise, some authors have studied the hip flexors, especially the psoas major, finding consistent results and relating them to performance in sprint running.[44,48] In contrast, in a recent study of all lower limb muscles, Sugisaki et al.[46] reported significant correlations between the MVs of the gluteus maximus and hamstrings and 100 m sprint time. In addition, other studies analysed the differences in muscularity between sprinters and non-sprinters, suggesting which muscles are more relevant to sprint performance, but again, showing some controversial results.[42,43,47] While Bex et al.[43] and Handsfield et al.[42] concluded that sprinters had larger quadriceps and hamstrings than non-sprinters, Ema et al.[47] only found differences in hamstrings and in adductors.

1.2.2 Assessment of muscularity

Skeletal muscle is highly adaptable and has consistently been shown to morphologically respond to exercise training. Skeletal muscle growth during periods of training has traditionally been referred to as skeletal muscle hypertrophy, and this manifests as increases in muscle mass, muscle thickness, muscle CSA, MV and muscle fibre CSA.[27]

The estimation of muscle size is essential to assess muscularity, hypertrophy or atrophy.[53] A wide range of techniques are employed to determine whole-muscle-size changes. One of the common methods for assessing muscularity is by quantifying muscle thickness. Muscle thickness is usually assessed by B-mode ultrasonography; a rapid, easy, relatively inexpensive and non-invasive test.[54] However, muscle thickness is only representative of one dimension of the muscle and the method is limited by a high standard error of the estimate.[27,55]

Dual-energy x-ray absorptiometry (DXA) was originally designed to measure bone mineral parameters and is now a widely used method for assessing skeletal muscle mass changes. DXA scans are reliable for assessing fat-free/bone-free lean tissue mass during whole-body scans,[27,56] nevertheless, they do not discriminate between muscle groups.[56] Notwithstanding, DXA can be used as a non-invasive assessment of gross and segmental lean whole-body mass.

Computed tomography can provide high-contrast, 2D images with pixel intensities related to tissue density, discriminating between muscle and other tissues.[27] Computed tomography is considered a reliable and valid method of assessing changes in muscle CSA.[27,57] A drawback to computed tomography scanning is that subjects are exposed to larger doses of radiation relative to DXA, along with it being expensive.[58]

Magnetic resonance imaging (MRI) is non-invasive, has excellent resolution, allows discrimination between separate muscles, and is commonly thought of as the reference standard for regional muscle mass assessment (Figure 1.5).[59] MRI is particularly useful for studying hydrogen-dense soft tissue, such as adipose tissue and skeletal muscle. For MRI-based volume assessments, a series of 2D cross-sectional slices are obtained and integrated as a function of distance to obtain volume. MRI assessments have yielded excellent reliability results.[59,60] Although these measures are the most accurate in terms of capturing changes in gross muscle size, MRI equipment is not widely accessible and the scans are costly; therefore, its use is scarcer in the literature. Furthermore, while MRI is considered the gold standard for assessing the 2-dimensional area or segmental volume of a particular muscle group, it does not glean molecular adaptations that occur within fibres (e.g., changes in contractile protein concentration, sarcoplasmic protein concentration, intra- versus extracellular fluid...).[61]

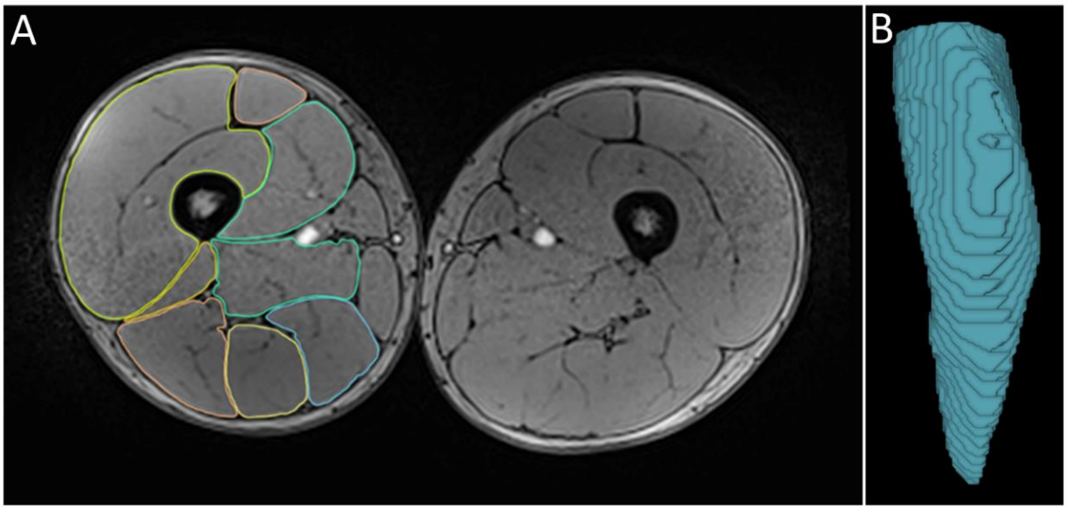

Figure 1.5 Thigh cross-sectional image and 3-D muscle reconstruction.

(A) Example of thigh cross-sectional image obtained by magnetic resonance imaging with manually outlined individual muscles perimeters and (B) the respective anterior view of the rectus femoris three-dimensional muscle reconstruction. (Unpublished data from our research group).

Traditionally, these methods have been used to quantify muscle thickness or CSA. As mentioned before, muscle thickness is only representative of one dimension of the muscle at one muscle location. CSA assessment is more accurate in measuring muscle size, since its representation of two-dimensions of the muscle and its determination using MRI are highly reliable. However, it is well known that exercise-induced muscle changes are not uniform along the muscle.[62] Thus, single muscle thickness or CSA measurement may not be representative of whole-muscle changes, given that different patterns of hypertrophy (ventral or distal) have been reported in response to different types of exercise.[63] New MRI approaches for the assessment of total MV and not only the CSA of particular sites of muscle, provide a better measurement of whole-muscle changes.[53] MV estimations require practitioners or clinicians to manually outline the muscles on several, if not all, images to assess their CSAs. This process is time consuming, which probably explains why many studies have provided only a single muscle thickness or CSA measurement to assess muscle size.[53]

1.2.3 Muscles analysed

In the present thesis the muscularity of the three main muscle groups of the thigh was analysed. In this section a brief anatomical and functional description of these muscle groups will be presented.

Quadriceps

The quadriceps femoris is a muscle group located in the thigh, comprising four muscles that form a large fleshy mass covering the front and sides of the thigh. It is the most powerful extensor of the knee, an assistant in hip flexion and plays an important role in knee joint stability. It is innervated by the femoral nerve (L2-L4). The quadriceps femoris is an extremely powerful muscle group, essential for motions such as walking, running, squatting and jumping. The name quadriceps femoris means ‘four-headed femoral muscle’, and the group consists of four individual muscles: the rectus femoris (RF), the vastus lateralis (VL), the vastus medialis (VM), and the vastus intermedius (VI). All these muscles have their own origin but all converge to form a common tendon, the quadriceps tendon, which becomes continuous with the patellar tendon (Figure 1.6).[64]

RF is the only muscle in the quadriceps femoris group that crosses both the hip and knee joints, and it is located in the midline, mainly in the superior part of the thigh. It originates in the anterior inferior iliac spine and at the superior margin of the acetabulum of the hip bone. It is the only hip flexor of the four, as well as being a knee extensor.[64–66]

VL is the largest component of the quadriceps muscle group and it is located at the side of the femur, forming the bulk of the lateral thigh. It originates at the great trochanter of femur and the linea aspera. Its function is knee extension.[64,67]

VM covers most of the medial aspect of the femur. It originates in the lower part of the intertrochanteric line of the femur and its function is knee extension, being especially active at the terminal phase of the extension. It is believed that VM plays the most determinant role in knee joint stability.[64,66,68]

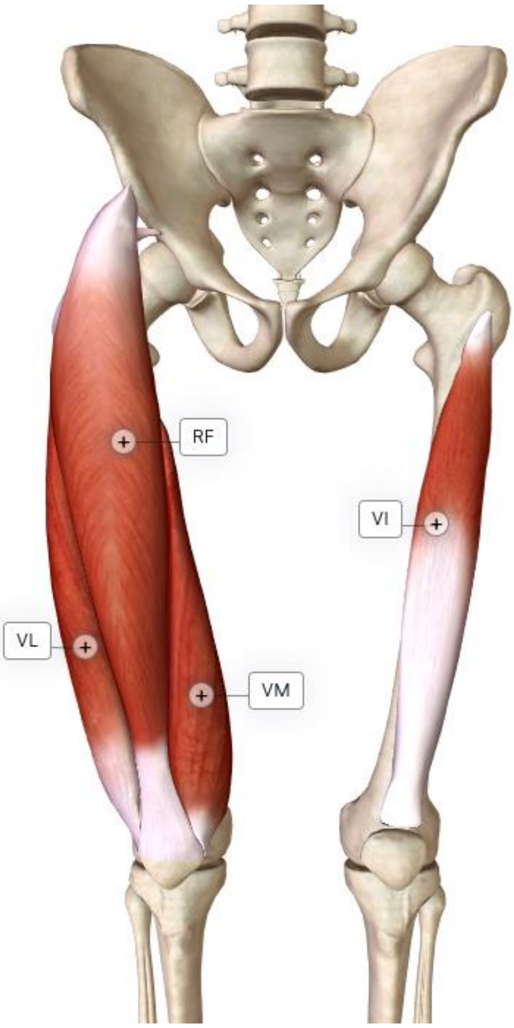

Figure 1.6 Quadriceps femoris muscle group.

Anterior view of the thighs with the four knee extensors, together forming the quadriceps muscle group. RF, rectus femoris. VL, vastus lateralis. VM, vastus medialis. VI, vastus intermedius. Note that VI lies underneath the RF. (Adapted from Human Biodigital).

VI lies under the RF, between VL and VM, almost entirely covered by the remainder of the quadriceps femoris muscles. It originates at the anterior superior part of the femoral shaft. VI and VL often appear fused together due to a lack of differentiation in some images.[64,66,67]

During sprint running the quadriceps muscle group is active during the whole stance phase and the early to mid swing phase. During the stance the four quadriceps are responsible for generating vertical GRFs through knee extension, first eccentrically to decelerate the CM and then concentrically to accelerate it again.[69,70] During the early swing the RF is still active in order to assist the hip flexion and drive the leg forward.[6,71]

Hamstrings

The hamstring muscle group is located at the posterior compartment of the thigh and crosses the hip joint and the knee joint, therefore, it is a hip extensor and the main knee flexor.[64,72] Four muscles are included in the hamstring muscle group; three bi-articular and one mono-articular. The three bi-articular muscles are the biceps femoris long head (BFlh), the semitendinosus (ST) and the semimembranosus (SM). The only mono-articular is the biceps femoris short head (BFsh). Due to insertions; SM and ST assist in thigh and leg internal rotation, and BFlh and BFsh assist in thigh and leg external rotation (Figure 1.7). The nerve innervation of the hamstrings is by the tibial division of the sciatic nerve (L5-S2) for the ST, SM and BFlh, and by the common fibular division of the sciatic nerve (L5-S2).[64,72,73]

ST is located medially in the posterior compartment and runs superficially to the SM. It arises from the posteromedial part of the ischial tuberosity by a shared tendon with the BFlh. Below mid-thigh the muscle belly rises to a tendon that attaches below the medial condyle of the tibia. The great length of the tendon gives the muscle its name.[64,73]

SM is also situated posterior-medially in the thigh, varies in size and has a flat and membranous shape. It originates from the superolateral of the ischial tuberosity, by a long flat tendon. The tendon descends underneath the BFlh and ST. The SM has more muscle belly in the inferior part of the thigh and attaches at the medial tibial condyle.[64,73,74]

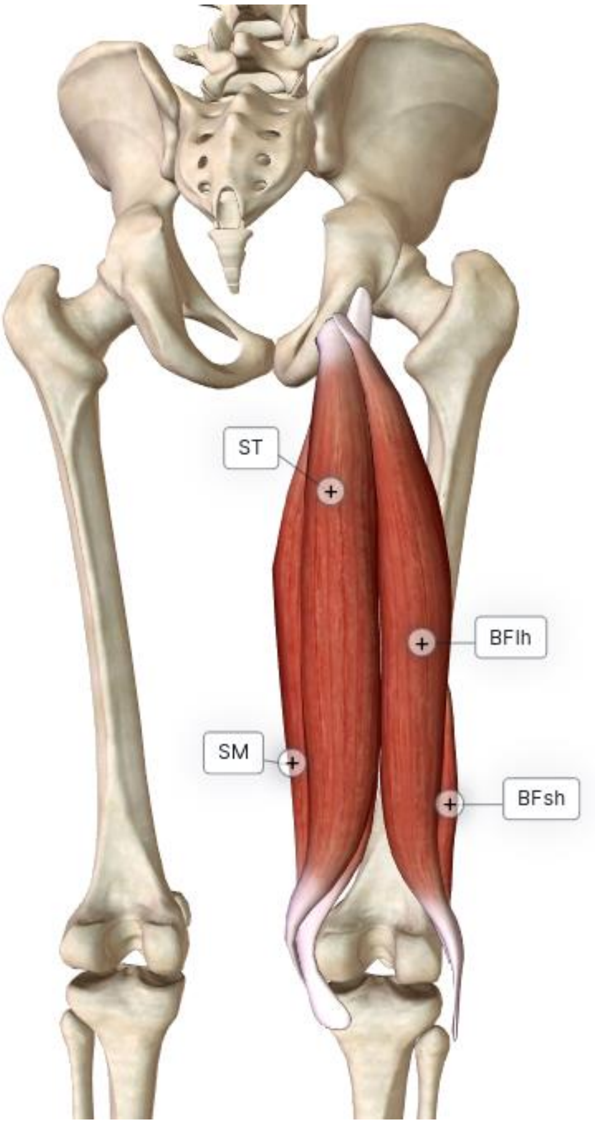

Figure 1.7 Hamstrings muscle groups.

Posterior view of the thighs with the three hip extensors and knee flexors, and the fourth knee flexor, together forming the hamstrings muscle group. ST, semimembranosus. SM, semimembranosus. BFlh, biceps femoris long head. BFsh, biceps femoris short head. (Adapted from Human Biodigital).

BFlh is located posterior-medially and arises from the inferior medial impression of the ischial tuberosity through a shared tendon with ST, then descends laterally and superficially to the thigh. BFsh originates from the femur at the lateral lip of the linea aspera at the posterior inferior mid-thigh and runs down deep and lateral on the thigh. BFlh crosses the sciatic nerve before forming an aponeurosis, and the BFsh joins with this aponeurosis on its deep surface. A common tendon is formed from this aponeurosis distally and inserts into the lateral aspect of the head of the fibula.[64,73]

The hamstring muscle group has a prominent role during sprinting and is quite susceptible to injury.[75,76] Hamstrings have peak activity from the mid swing until the terminal stance.[70,72] Firstly, in the mid and late swing, they work eccentrically to decelerate the knee extension (produced by quadriceps) and during the whole stance they work concentrically, as hip extensors, to produce forward motion.[72,75,77]

Adductors

The adductor muscle group is part of the inner hip musculature and ranges from the lower pelvic bone to the femur and knee region. The adductors shape the surface anatomy of the medial thigh, and lie between the extensor (quadriceps) and flexor (hamstring) groups of the thigh muscles.[64] Adductor muscle group is made up of adductor magnus, adductor longus, adductor brevis, adductor minimus, pectineus and gracilis (Figure 1.8). Their main function is adduction of the hip and stabilisation of the pelvis, however, these individual muscles have functions other than adduction. All muscles are innervated by the obturator nerve or its direct branches, except the pectineus, which is innervated by the femoral nerve and part of the adductor magnus, innervated by the tibial nerve.[64]

Adductor magnus is by far the largest of the hip adductor muscles and consists of two parts; the adductor and the ischiocondylar parts. The adductor part originates from the inferior pubic ramus and inserts at the gluteal tuberosity and the medial lip of the linea aspera.[64] The ischiocondylar part originates from the ischial tuberosity and inserts at the medial epicondyle of the femur.[64,78] Along with hip adduction, adductor magnus is a powerful hip extensor, especially when the hip is flexed.[79,80] Moreover, it assists hip flexion and hip internal and external rotation, due to its two parts.[78,81]

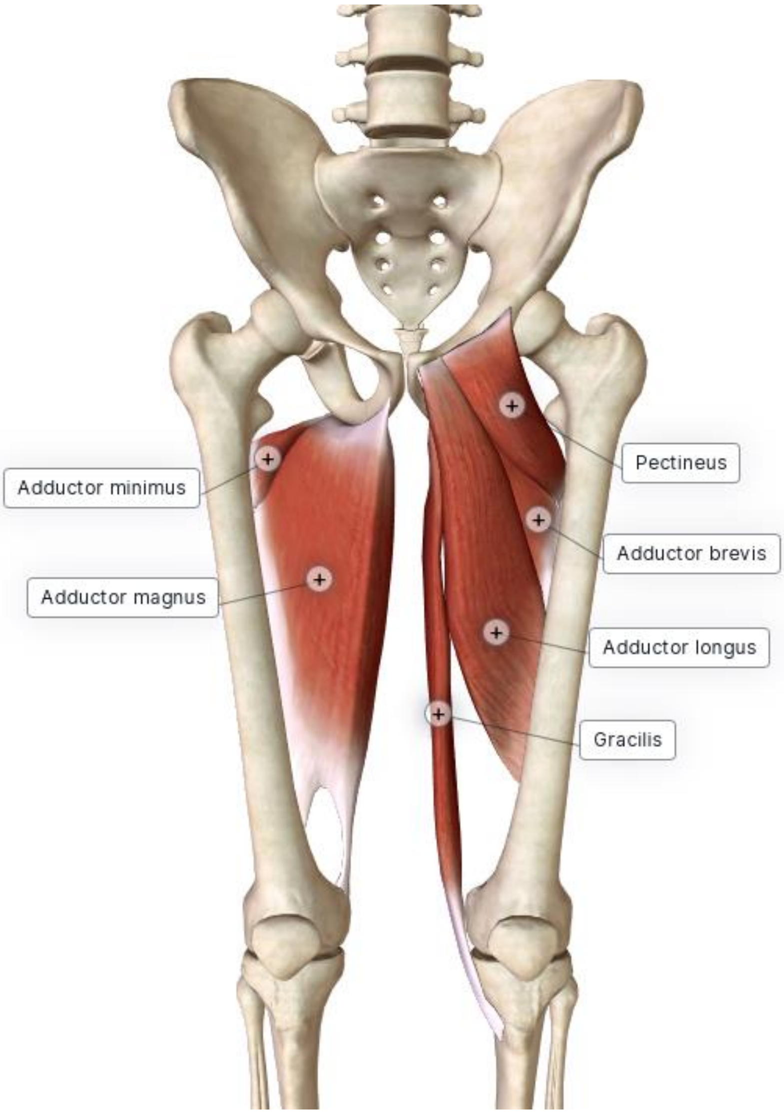

Figure 1.8 Adductor muscle group.

Anterior view of the thigh with the six medial muscles, together forming the hip adductor muscle group. (Adapted from Human Biodigital).

Adductor longus has its origin at the external surface of the pubic bone and inserts at the medial lip of the linea aspera. Distally, it forms an aponeurosis extending to the VM.[64,82] The functions of adductor longus are hip adduction and hip flexion and it assists with hip external rotation.[64,81]

Adductor brevis originates at the inferior pubic ramus and inserts at the pectineal line and upper third of the medial lip of the linea aspera.[64] The actions of the adductor brevis are hip adduction and hip flexion.[81]

Adductor minimus has its origin in the inferior pubic ramus and its insertion in the gluteal tuberosity of the femur.[64] This muscles may be partially or wholly separated from the adductor magnus which is found in many people. Adductor minimus is a hip adductor and it helps with the external rotation of the hip.[81]

Pectineus has its origin on the superior ramus of the pubis, on the pectineal line, and it inserts on the posterior aspect of the proximal femur, at the pectineal line of the femur.[64] The pectineus muscle is a hip adductor and assists hip flexion.[81]

Gracilis runs from the external and inferior ramus of the pubis and inserts at the medial and superior part of the tibia.[64] It is the most superficial medial of the adductors and its tendon is easy to palpate in the inguinal region. Gracilis is mainly a hip adductor and assists with hip flexion, knee flexion and internal leg rotation.[81]

Great activity of the adductor muscle group has been reported during sprinting.[70,71] In the early swing, where hip flexors are stretched, adductors play an important role to assist hip flexion and to neutralise the abduction and external rotation caused by tensor fascia latae and sartorius. During the mid to late swing, when the leg is bent and the gluteus maximus starts the hip extension, adductors work as a synergist of gluteus maximus helping with hip extension and counterbalancing the external rotation of the gluteus maximus.[70]

2 RESEARCH AIMS

2.1 Aims

2.1.1 General aims

The aims of this thesis were (I) to analyse the influence of thigh muscularity on sprint performance in different populations, and (II) to study the adaptation of these muscles after a sprint-training period in national-level sprinters.

2.1.2 Specific aims

1. To determine and compare MVs, as well as SMPs and sprint performance between recreationally trained males and national-level sprinters (Study I).
2. To determine and compare MVs, as well as SMPs and sprint performance between male and female national-level sprinters (Study II).
3. To study relationships between thigh MVs, SMPs and sprint performance (Studies I, II, III).
4. To study the effect of a 5-month sprint-based training macrocycle on sprint performance, thigh MVs and SMPs in national-level sprinters (Study III).

2.2 Hypothesis

2.2.1 Study I: Sprinters vs. recreationally trained males.

1. Sprinters are faster and have greater SMPs than recreationally trained males.
2. Sprinters have larger thigh MVs than recreationally trained males.
    a. Hamstrings MV is disproportionately greater in sprinters compared with recreationally trained men.

3. Hamstrings MV is associated with sprint performance in national-level sprinters and recreationally trained males

2.2.2 Study II: Male vs. female sprinters.

1. Male sprinters are faster than female sprinters and present greater SMPs.
2. When normalised by height-mass, male and female sprinters show no difference in thigh MVs.
3. Hamstrings MV is associated with sprint performance in female and male national-level sprinters.
4. Adductors MV is associated with sprint performance, but to a lesser extent than hamstrings MV.

2.2.3 Study III: Effects of sprint training.

1. After 5 months of sprint-specific training, highly trained athletes are able to significantly improve their sprint performance.
2. After 5 months of sprint-specific training, all thigh MVs increase significantly, but the increase in hamstring and adductor MV is greater than in quadriceps.
3. All SMPs increase after 5 months of sprint training.

3 METHODS

This thesis presents data from three consecutives studies. Sprint performance, thigh MVs and SMPs were assessed by cross-sectional studies (Studies I and II) and by an ecological follow-up of a real-world training study (Study III). Here, the methods used in all the studies are summarised. For further details, the reader is referred to the corresponding study.

3.1 Participants

Twenty-two males and eight females gave written, informed consent to participate in the experiments. The main characteristics of the subjects are displayed in Table 3.1.

Study	**Subjects**	**n**	**Sex**	**Age** (years)	**Mass** (kg)	**Height** (m)
I	Recreational-trained adults	9	Male	24.3 ± 4.3	74.4 ± 4.6	1.78 ± 0.07
	National-level sprinters	7	Male	24.1 ± 2.8	74.2 ± 8.0	1.80 ± 0.07
II	National-level sprinters	8	Female	23.9 ± 5.3	57.0 ± 6.9	1.63 ± 0.08
		9	Male	23.3 ± 1.7	73.8 ± 8.6	1.80 ± 0.07
III	National-level sprinters	6	Female	24.9 ± 5.3	55.7 ± 6.9	1.63 ± 0.08
		6	Male	21.8 ± 1.5	74.4 ± 8.6	1.81 ± 0.07

Table 3.1 Participants' characteristics from the thesis.

Main characteristics of the participants from the three studies comprising the thesis (mean ± standard deviation).

3.1.1 Ethical approval of research

The studies complied with the standards of the World Medical Association (Declaration of Helsinki) and approval was given by the Ethics Committee of the Catalan Sports Council (Generalitat of Catalonia) (0099S/690/2013).

3.2 Study design

In order to determine differences in baseline condition (without training interference effects) Study I and Study II had a cross-sectional design: first, comparing sprinters and non-sprinters (Study I) and second, comparing male and female sprinters (Study II) (Figure 3.1). Both studies were carried out between the end of the sprinters' off season (Study I) and the very beginning of the pre-season (Study II), where sprinters had between 6 and 8 weeks of rest and functional and morphological adaptations had not yet occurred.

In contrast, in Study III, a group of sprinters were screened during a 5-month indoor training macrocycle (Figure 3.1). The rationale behind using the winter macrocycle instead of the summer macrocycle was because we were interested in analysing the training effect from the baseline values, and summer macrocycle starts in a highly trained condition, with all adaptations from the indoor cycle. Moreover, the goal of the study was to analyse the training effect in real-training conditions, therefore, ecological follow-up methodology (with no interference of training) was chosen for Study III. During the indoor macrocycle the sprinters were analysed on three different occasions; at the beginning, in the middle and at the end of the training period.

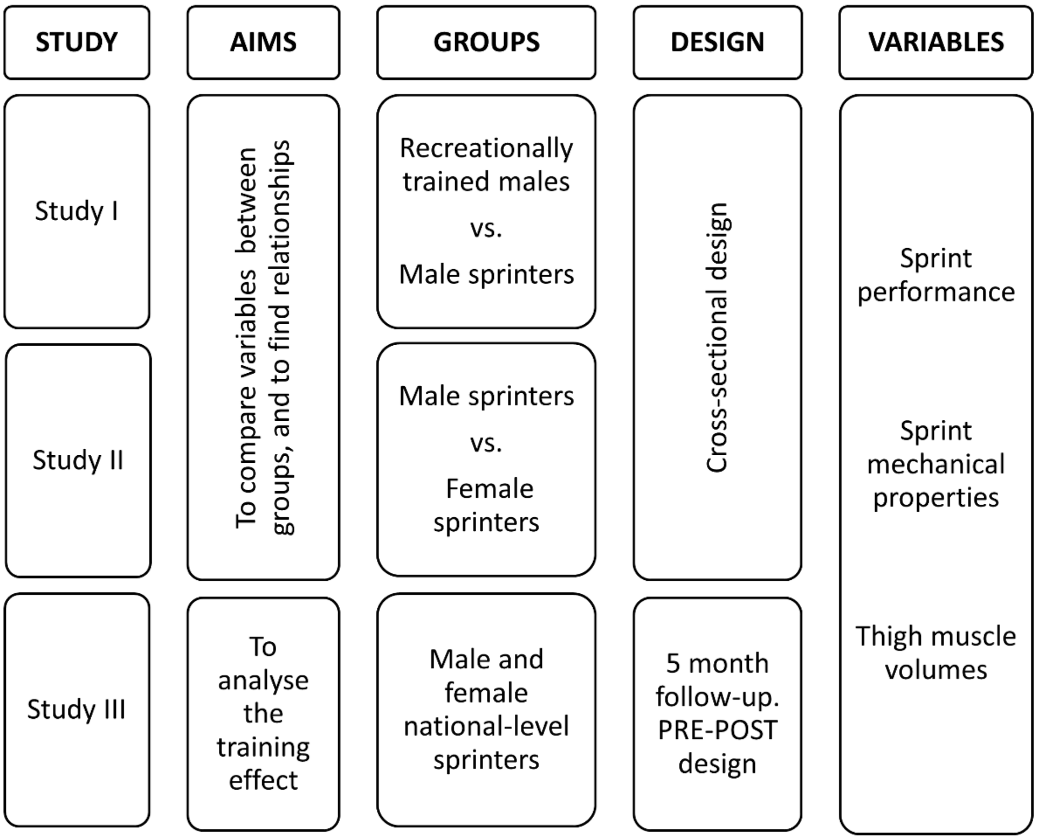

Figure 3.1. Schematic overview of the design of the thesis.

Schematic overview of studies, aims, participants, designs and variables analysed from the three studies comprising the thesis.

3.3 Sprint performance

A wide spectrum of maximal anaerobic power distances was used to assess sprint performance in the different studies, and it was determined by the time taken to cover the distance in seconds and hundredths of a second. 10 and 40 m; 40 and 80 m; and 10, 40, 80, 150 and 300 m were used in Studies I, II and III, respectively, as indicators of sprint performance. Moreover, two different methodologies to measure sprint performance were used. In Study I performance was assessed using a radar device (Stalker ATSII, Plano, Texas, USA) at 48 Hz, and in Studies II and III using wireless photocells (Microgate Witty, Microgate, Italy) at 1000 Hz.

When using the radar to assess sprint performance, the athlete was placed right before the 0 m mark (starting line). The device was placed on a tripod, 2 m behind the participants, at a height of 1 m, to align with the averaged subjects' CM (Figure 3.2). The radar measures the forward sprinting velocity of the subject at a sampling rate of 48 Hz. The sprint times were taken from the modelled running speed in hundredths of a second (see SMPs section/formulae, page 61).

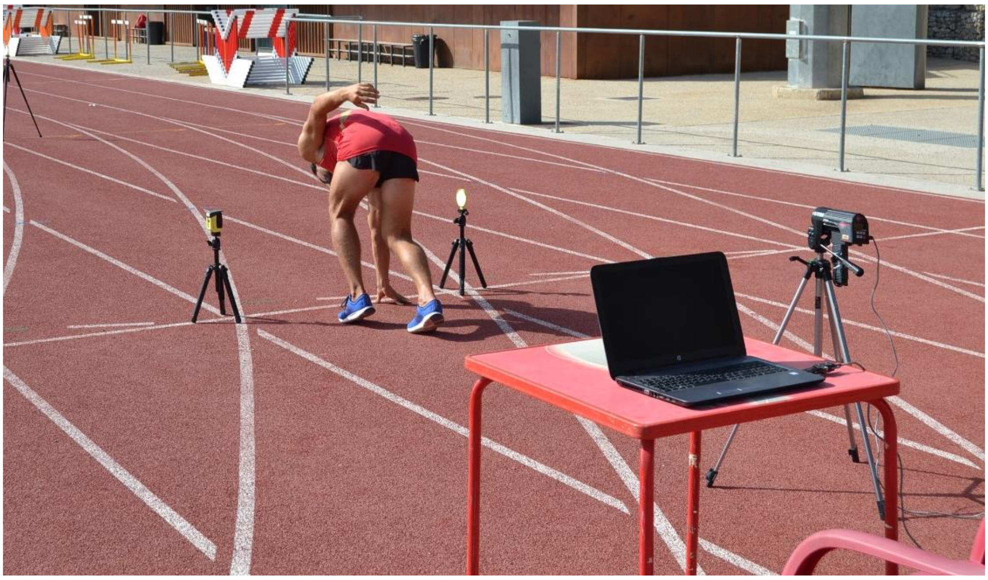

Figure 3.2. Radar device.

Graphical representation of the method used to asses sprint performance and sprint mechanical properties using a radar device (Stalker ATSII, Plano, Texas, USA) to compute horizontal speed as a function of time.

When using photocells, the athlete started his attempt just before the first photocell, and at the very first moment the timer was started (Figure 3.3). Every time the athlete crossed the next photocell, the time was recorded in thousandths of a second. A pair of photocells were placed at the 0 m mark (starting line) and at any other desired distance, for each sprint recorded.

Regardless of the distance, subjects performed the maximal sprints after the standardised warm-up (see different studies). The starting position was the three-point start, with both feet on the floor, one hand (the contralateral of the advanced leg) in contact with the ground, and the other hand held up behind the back and above the hip. The participants were told to start when they liked, in order to have a faster and more reliable start. For relatively short distances (from 10 to 80 m) athletes performed two attempts at each distance and the fastest trial was used for further analysis. For relatively long distances (150 m and 300 m) athletes performed just one attempt. Different passive rest times were given to the athletes depending on the sprint distance (see different studies). In Study I subjects wore their usual training shoes (no athletic spikes were used) and in Studies II and III sprinters used spikes. All tests were performed on a Tartan Track surface in a track stadium.

Figure 3.3. Wireless photocells.

Graphical representation of the method used to assess sprint performance using wireless photocells (Microgate Witty, Microgate, Italy) to compute sprint times with the athlete using a three-point start position.

3.4 Sprint mechanical properties

To compute SMPs a recently validated method from Samozino et al.[24] was used. This approach is similar to those proposed by Furusawa et al.[83] and Vandewalle and Gajer.[84] The present computation method is built on the measurement of simple velocity-time data via sports-radar devices. Such an approach makes several assumptions: (1) the entire body is represented in displacement of the runner's body CM; (2) when averaged across the acceleration phase, no vertical acceleration occurs during a sprint; and (3) the coefficient of air drag remains constant. During maximal acceleration sprinting, a horizontal velocity-time curve has been shown to systematically follow a mono-exponential function for recreational to highly trained sprinters.[24,83,85] This mono-exponential function is applied to the raw velocity-time data (Figure 3.4). After this, the fundamental principles of dynamics in the horizontal direction enable the net anteroposterior GRF to be modelled for the CM over time, considering the mass of the athlete and constant aerodynamic friction of the body in motion. Force and velocity are then plotted to determine F-V relationships and later, P-V relationships. All variables used to compute this method are modelled over time, without considering intra-step changes, thus corresponding to step-averaged values (contact plus aerial times).

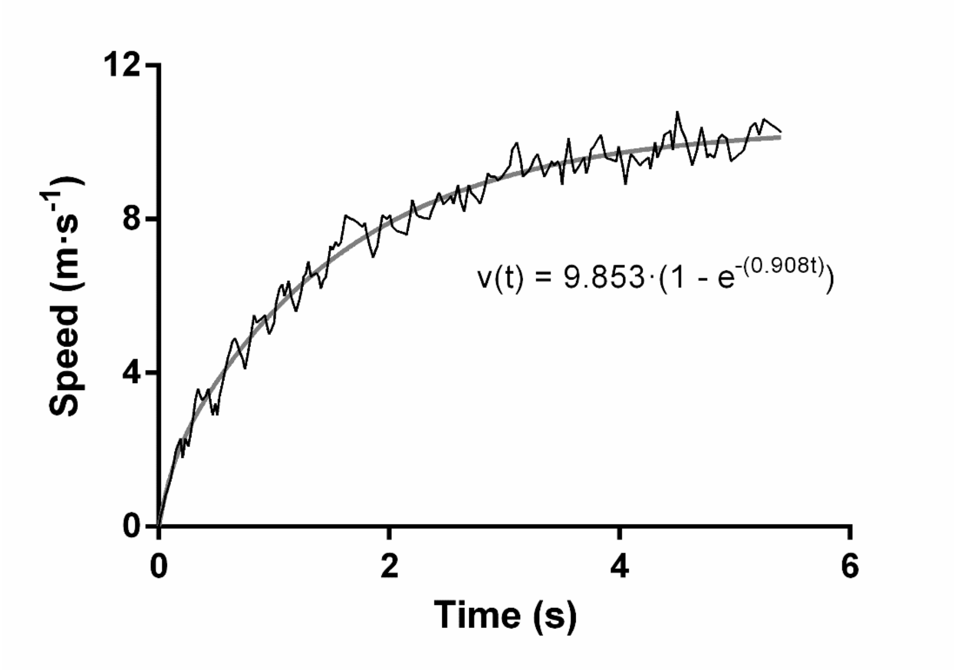

Figure 3.4 Speed-time curve

Example of a speed-time curve measured by the radar (black line) and modelled by the mono-exponential function (grey line) corresponding to the equation.

Instantaneous velocity over a distance of 40 m was measured by radar (Stalker ATSII, Plano, Texas, USA) with a sampling rate of 48 Hz. The device was placed on a tripod, 2 m behind the participants, at a height of 1 m, to align with the averaged subjects' CM (Figure 3.2). The starting position was the three-point start. Subjects were instructed to keep static in the starting position for about one second, in order to record a "0 velocity" signal, and then to start running forward without any countermovement. In Study I subjects wore their usual training shoes (no athletic spikes were used) and in Studies II and III sprinters used spikes. All tests were performed on a Tartan Track surface in a track stadium. Two attempts per subject were recorded at each time point, with six minutes of rest between trials. The best attempt was selected for further analysis. Data were analysed post hoc using R Studio software v0.99.489 (RStudio, Boston, Massachusetts, USA) to compute sprint F-V profiles. Raw values for horizontal velocity (v_h) and time (t) in the acceleration phase were adjusted to an exponential function using least-square regression [85]. This model has been shown to have a strong fit with data from recreational to high level athletes:

$$v_h(t) = v_h max \cdot \left(1 - e^{-\frac{t}{\tau}}\right) \quad [1]$$

Where $v_h\ max$ is the maximal velocity reached at the end of the acceleration and τ is the acceleration time constant. The horizontal position (x_h) and acceleration (a_h) of the body CM as a function of time can be expressed as follows:

$$x_h(t) = v_h max \cdot \left(t + \tau \cdot e^{-\frac{t}{\tau}}\right) - v_h max \cdot \tau \quad [2]$$

$$a_h(t) = \left(\frac{v_h max}{\tau}\right) \cdot e^{-\frac{t}{\tau}} \quad [3]$$

Applying the fundamental laws of dynamics in the horizontal direction, the net anteroposterior GRF (F_h) applied to the body CM can be modelled over time as:

$$F_h(t) = m \cdot a_h(t) + F_{aero}(t) \quad [4]$$

Where m is the runner's body mass (in kg) and F_{aero} is the aerodynamic friction coefficient, which can be estimated as proposed by Arsac and Locatelli[86] from values of air density (ρ_0, in kg/m^3), frontal area of the runner (Af, in m2), and drag coefficient (Cd = 0.9):[87]

$$k = 0.5 \cdot \rho \cdot Af \cdot Cd \quad [5]$$

With,

$$\rho = \rho_0 \cdot \frac{Pb}{750} \cdot \frac{273}{273 + T^{º}} \quad [6]$$

$$Af = (0.2025 \cdot h^{0.725} \cdot m^{0.425}) \cdot 0.266) \quad [7]$$

Where ρ_0 = 1.293 kg·m^{-1} is the ρ at 760 Torr and 273 ºK, Pb is the barometric pressure (in Torr), $T^{º}$ is the air temperature (in Cº), and h is the runner's stature (in m). The mean net horizontal anteroposterior power output applied to the body CM (Ph in W) can then be modelled at each instant as the product of F_h and v_h. The F-V relationship was modelled using least-square linear regression, and extrapolated to obtain F_0 and V_0 as the intercepts of the F-V line with the force and velocity axes, respectively.[18] F_0 is the maximal theoretical horizontal force produced and corresponds to the runner's initial push. V_0 is the maximal theoretical running velocity and represents the capability to produce horizontal force at very high running velocities.[88] Maximal power ($Pmax$) values were computed as follows:[23]

$$Pmax = \frac{F_0 \cdot V_0}{4} \quad [8]$$

In the vertical direction, the runner's body CM during the acceleration phase of a sprint goes up from the starting crouched position (be it with or without using starting blocks) to the standing running position, and then does not change from one complete step to the next. Because the initial upward movement of the CM is attenuated over a relatively long time/distance (~30-40 m),[89,90] it can be considered that it does not require any great vertical acceleration and so the mean net vertical acceleration of the CM over each step is quasi-null throughout the sprint acceleration phase. Consequently, applying the fundamental laws of dynamics in the vertical direction, the mean net vertical GRF (F_v) applied to the

CM over each complete step can be modelled over time as equal to body weight:[91]

$$F_v(t) = m \cdot g \qquad [9]$$

Where g is the gravitational acceleration (9.81 m·s^{-1}).

Morin et al.[8] proposed that the mechanical effectiveness of force application during running could be quantified over each support phase by the ratio (RoF in %, Eqn. [10]) of F_h to the corresponding total resultant GRF (F_{res}, in N) (Figure 1.4):[24]

$$RoF = \frac{F_h}{GRF} \cdot 100 = \frac{F_h}{\sqrt{{F_h}^2 + {F_v}^2}} \cdot 100 \qquad [10]$$

Then, the mechanical index of force application technique or D_{RF} can be defined as the rate of decrease in R_oF with increasing speed during sprinting (D_{RF}, in %·s·m^{-1}), and is computed as the slope of the linear R_oF-velocity relationship. The D_{RF} describes the athlete's capability to limit the inevitable decrease in mechanical effectiveness with increasing speed, and it can be understood as an index of the ability to maintain a net anteroposterior force production despite increasing running velocity. The more negative the slope, the faster the loss of effectiveness of force application during acceleration, and vice versa.[88]

To date, R_oF values have been computed from the second step (i.e., the first complete step) to the step at maximal speed.[8,18,24] Because the starting block phase (push-off and following aerial time) lasts around 0.5 s and so occurs at an averaged time of ~0.3 s,[24,90] R_oF and D_{RF} can be reasonably computed from F_h and F_v values modelled from t > 0.3 s.[24]

3.5 Muscle volumes

MRI was used to compute the 3-dimensional volumes of the individual muscles of the thigh. A series of cross-sectional images of each subject's thigh were obtained using an MRI Avanto 1.5T (Magnetom Avanto, Siemens Healthineers, Germany) (Figure 3.5). Transaxial images (slice thickness, 2mm; increment, 2mm) were acquired in a 320x320 matrix, 40x40 field of view in 20-second blocks. Participants were placed supine and symmetrically inside the scanner with their heads outside the MR-bore and the thighs covered by one 32- and two flexible 4-channel coils, respectively, in the proximal and distal segments. A custom-made foot-restraint device was used to standardise and fix limb position, and to avoid any compression of thigh muscles. To ensure the same anatomical area was assessed in each temporal point (Study III), the range was centred at the mid-length of the femur, measured on the coronal plane image. Between 280 and 320 images (depending on each subject's thigh length) of both legs were obtained from the iliac spine to the patella. In all three studies, MRI acquisition was performed with at least 48 h of recovery after the previous training session, to account for hypertrophic changes and avoid any influence of acute muscle swelling.[92]

Figure 3.5 Magnetic resonance imaging scan.

Magnetic resonance imaging device Avanto 1.5T (Magnetom Avanto, Siemens Healthineers, Germany) from Creu Blanca radiology services, used in the present thesis to compute muscle volumes.

Two different approaches were taken for the MV assessment.

In Study I the edges of RF, VM, VL + VI (VLI), BFlh, BFsh, ST and SM muscles were manually outlined image-by-image from the dominant leg (chosen as the front leg in the starting block position). Because substantial fusion may be found between VL and VI on some slices,[53] these muscles were outlined together as VLI. Quadriceps MV was calculated by the sum of RF, VM and VLI, and hamstrings MV by the sum of BFlh, BFsh, ST and SM. (Figure 4.2)

In contrast, in Studies II and III, the edges of VL, VI, VM and RF were outlined together and identified as quadriceps. BFlh, BFsh, ST and SM were outlined together and identified as hamstrings. MV results of Studies II and III are shown as the average of right and left thighs (Figures 5.1 and 6.2).

For the assessment of adductors MV, which included adductor magnus, adductor longus, adductor brevis, adductor minimus, pectineus and gracilis, the edges of these muscles were digitalised together and computed as adductors. Identification of individual adductor muscles is difficult due to the fusion of some muscle along the thigh,[47] therefore, the adductor muscle group was outlined together in all three studies.

In order to minimise errors of measurement in calculating MVs, we used the reference method to analyse MVs proposed by Nordez et al.[53] Regardless of the study and the muscle (or muscle group) analysed, the edges of the muscles were outlined in every single slice (280 to 320 depending on the subject's thigh length), by the same researcher, using OsiriX 8.5.2. (Pixmeo, Geneva, Switzerland), similarly to previous studies.[93] The total volume of each muscle was calculated in the range between the last image where the ischial tuberosity was visible to the last image where the muscle was visible. The intra-investigator coefficient of variation for muscle segmentation was between 1.1 ± 0.4% and 1.0 ± 0.05% for the muscles assessed; similar to previous estimations of error using this method.[53,93]

3.6 Statistical analyses

Data were tested for approximation to a normal distribution using the Shapiro-Wilk test. Asymmetrically distributed data were log- or sqrt-transformed before analysis.

In Studies I and II an independent sample T-test was performed to compare the different variables between groups. In Study III a one-way repeated measure analysis of variance (ANOVA) was used to identify the effect of time on the different variables analysed. If significant effects were found, a post-hoc Bonferroni corrected paired t-test was applied to identify significant differences between the pre, during and post values.

To assess the differences between groups the comparisons were also determined via standardised mean differences (Cohen's d) and respective 90% confidence interval (CI) (lower limit : upper limit). Thresholds for effect size (ES) statistics were: 0.2, trivial; 0.6, small; 1.2, moderate; 2.0, large; 4.0, very large; and > 4.0, extremely large.[94]

Associations between variables of interest were assessed using Pearson's correlation coefficient, with thresholds being: 0.40-0.59, moderate; 0.60-0.79, strong; 0.80-1, very strong.

Data are presented as mean ± standard deviation (SD). The level of significance was set at $P < 0.05$.

The statistical analysis was conducted using SPSS version 23.0.0.0 (SPSS Statistics, IBM corp., Armonk, New York, USA).

4 STUDIES

4.1 Study I

Sprinters vs. recreationally trained males.

4.1.1 Abstract

The purpose of this study was to compare mechanical properties and performance in sprint running, as well as thigh MVs, between national-level sprinters and recreationally trained subjects (actives), and to establish relationships between MVs and performance parameters. Seven male sprinters and nine actives performed maximal-effort 40 m sprints. Instantaneous velocity of sprint running was measured by radar to obtain F_0, V_0 and P_{max}. For MV assessment, a series of cross-sectional images of each subject's thigh were obtained by MRI for RF, VM, VLI, BFlh, BFsh, ST, SM and the adductor muscle group. Sprinters were faster over 10 m (7%, ES = 2.12, $P < 0.01$) and 40 m (11%, ES = 3.68, $P < 0.01$), and showed significantly higher V_0 (20%, ES = 4.53, $P < 0.01$) and P_{max} (28%, ES = 3.04, $P < 0.01$). Sprinters showed higher quadriceps MV (14%, ES = 1.12, $P < 0.05$), adductors (23%, ES = 1.33, P < 0.05) and, especially, hamstrings MV (32%, ES = 2.11, $P < 0.01$), than actives. Hamstrings MV correlated strongly with 40 m sprint time ($r = -0.670$, $P < 0.01$) and V_0 ($r = 0.757$, $P < 0.01$), and moderately with P_{max} ($r = 0.559$, $P < 0.05$). Sprinters were significantly faster and exhibited greater SMPs compared to trained males. Larger MVs were found in sprinters' thighs, especially in the hamstring musculature, and strong correlations were found between hamstrings MV and SMPs and sprint performance.

Keywords: *muscle volume, hamstrings, acceleration, sprint performance, sprint mechanical properties*.

4.1.2 Introduction

In team sports, acceleration capacity is crucial for performance, due to the short and multidirectional movements. By contrast, in track and field events, with longer distances, sprint performance is determined by acceleration capacity and maximum velocity. Although many factors may influence sprint performance, recent literature has shown that the ability to produce large amounts of anteroposterior GRF is the strongest predictor of acceleration and sprint performance, regardless of the level.[10,18,24,75] The overall mechanical capability to produce and apply horizontal force throughout the sprint is well described by the inverse linear F-V and parabolic P-V relationships, which characterise the mechanical limits of the entire neuromuscular system.[24] These individual F-V relationships describe the changes in horizontal force generation with increasing running velocity and are summarised by the following variables: F_0, V_0 and P_{max}.[24,76] As the relationship between these variables encompasses the entire capability of the neuromuscular system, it is inclusive of the mechanical properties of individual muscles, morphological features, and neural mechanisms underpinning motor-unit drive. Moreover, these variables integrate the ability of the given athlete to orient the GRF horizontally.[8,24]

Sprinting is a complex movement pattern where the body mass of the athlete is propelled forward by propulsive forces produced by lower limb joint torques.[46] It is known that MV is the major determinant of joint torque in humans,[37] hence, it can be hypothesised that MV plays an important role in sprint performance. When comparing sprinters to the average population, the differences in muscularity are noticeable.[42,43] Since larger muscles will produce greater force and power,[37,42,43] it might be expected that extremely large muscles are advantageous for sprint performance. However, we should be cautious with this supposition since enlargement of a muscle increases the moment of inertia of the segment and, hence, reduces the limb’s angular acceleration for any given joint torque.[42,46] Many studies have investigated the relationship between muscularity and sprint performance,[41,44,95,96] using muscle thickness and/or muscle CSA, usually finding positive relationships between them. Nevertheless, it is known that changes in muscle shape are not uniform along the muscle, and this fact exposes the limitations of a single measure, which might not be sufficient to accurately quantify hypertrophic changes.[42,46,62] Thus, adopting MV instead of muscle thickness or CSA as a measure of muscularity could be more accurate for understanding sprint adaptations and their relationship with performance[46]. Moreover, examining different muscles is important to elucidate which muscles are crucial for achieving higher speeds and to make informed decisions regarding training.

Thus, the purpose of this study was to determine and compare SMPs and sprint running performance, as well as thigh MVs, between recreationally trained subjects and national-level sprinters. Additionally, the relationships between thigh MVs and SMPs and performance were investigated.

4.1.3 Methods

Participants

Seven male sprinters and nine male sports science students volunteered to participate in this study (Table 4.1.1). Sprinters' personal best times over 100 m ranged from 10.48 to 11.25 s, attained within the last 2 years. The sports science students were physically very active (7.9 ± 2.2 h of training per week), including strength training and a wide variety of team sports, at recreational level, but they were not engaged in any federated sport at that moment. All participants were healthy and free of any lower limb musculoskeletal or neuromuscular injuries from the 6 months prior to the study. The experiment was conducted in accordance with the code of ethics of the World Medical Association (Declaration of Helsinki) and approved by the Ethics Committee of the Catalan Sports Council (Generalitat de Catalunya) (0099S/690/2013).

Design

A cross-sectional study was designed to investigate differences in SMPs and performance, and thigh MVs, between sprinters and physically active subjects, and to examine possible relationships. All testing occurred during the very beginning of the (sprinters') pre-season, where sprinters were not at their prime and hypertrophic and performance changes had not taken place. MRI and sprint tests were performed on Mondays with at least 72 h of rest for both groups. Actives performed a familiarisation session of sprinting one week before the study.

Anthropometric characteristics

In order to exclude differences in body composition and body segment sizes between sprinters and actives that could affect the interpretation of thigh MVs, an anthropometric analysis was implemented. All anthropometric measurements were performed by the same researcher, according to the standard criteria of the International Society for the Advancement of Kinanthropometry (ISAK).[97] Eight skinfold thicknesses were measured to estimate the percentage of body fat, using the equations of Withers et al.[98]

Sprint mechanical properties and performance

Instantaneous velocity over a 40 m sprint was measured by radar (Stalker ATSII, Plano, Texas, USA) with a sampling rate of 48 Hz, which has been previously validated in human sprint running experiments [18,24]. The device was placed on a tripod, 2 m behind the subjects, at a height of 1 m, to align with the averaged subjects' CM. Subjects adopted the three-point starting position and they wore their usual training shoes (no athletic spikes were used). Subjects were instructed to keep this static position to record a zero velocity. Moreover, in order to achieve a faster and more reliable start, they were told to start at will, when they wanted to. All tests were performed on a Tartan Track surface in a track stadium. The warm-up consisted of 5 min of light jogging, followed by 5 min of articular mobilisation and active stretching, then 10 min of sprint-specific warm-up exercises and three progressive runs over 40 m interspersed by 3 min of passive rest. Two sprint trials per subject were recorded with 6 min of passive rest between trials. The fastest trial, based on sprint time, was selected for further analyses. The resultant data were subsequently analysed using the simple field method validated by Samozino et al.[24] Briefly, this computation method is based on a macroscopic inverse dynamics analysis of the CM motion. Velocity-time data are fitted by an exponential function, after which instantaneous velocity is derived to compute the net anteroposterior GRFs, power and sprint performance (defined as 10 m and 40 m sprint times). Individual linear F-V relationships were then extrapolated to calculate F_0 and V_0 capabilities and underlying P_{max}, as described elsewhere (Figure 4.1.1).[18,24]

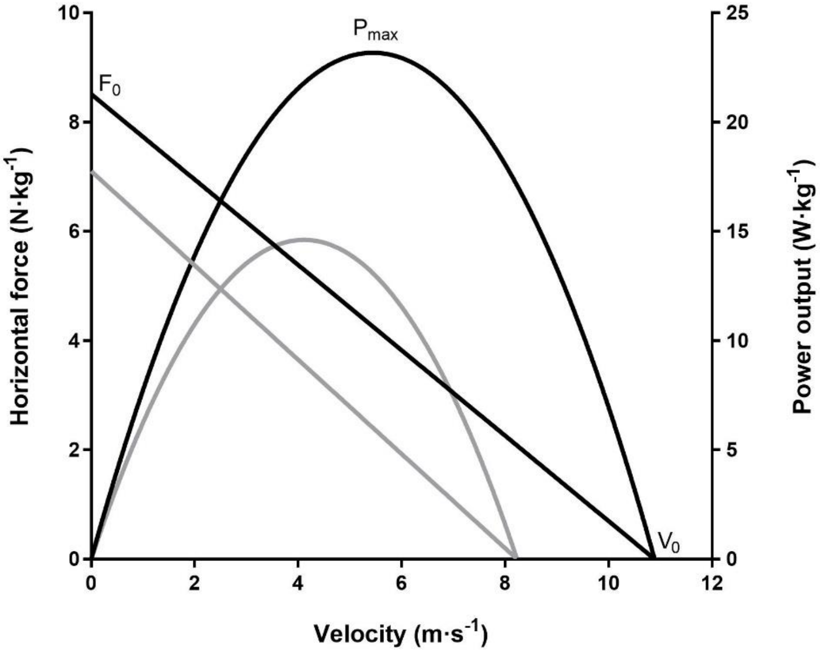

Figure 4.1.1 Representative power-force-velocity profile from Study I.

A graphical representation of linear force-velocity and 2nd degree polynomial power-velocity relationships of 1 representative volunteer from each group (grey lines [active] vs. black lines [sprinter]) over a 40 m maximal overground sprint. F_0*, theoretical maximal horizontal force.* V_0*, theoretical maximal horizontal velocity.* P_{max}*, maximal horizontal power.*

Muscle Volume

For MV assessment, series of cross-sectional images of each subject's thigh were obtained by MRI with an Avanto 1.5T (Magnetom Avanto, Siemens Healthineers, Germany). Transaxial images (slice thickness, 2 mm; increment, 2 mm) were acquired in a 320x320 matrix, 40x40 field of view with 20 second blocks. The volunteers were placed supine inside the scanner with the head outside the MR bore, thighs covered with a leg coil and limb position fixed with a custom-made foot restraint. Between 280 and 320 (depending on each subject's thigh length) images of both legs were obtained from the iliac spine to the patella. Scans were performed with at least 72 h of recovery after the previous training session to avoid any influence of acute exercise-induced muscle swelling.[92]

The edges of RF, VM, VLI, BFlh, BFsh, ST and SM muscles were manually outlined image by image by the same researcher using OsiriX 8.5.2. (Pixmeo, Geneva, Switzerland) similarly to previous studies[93] (Figure 4.1.2). The adductor muscle group was outlined as one and includes adductor magnus, adductor longus, adductor brevis, adductor minimus, pectineus and gracilis. The total volume of each muscle was calculated in the range between the last image where the ischial tuberosity was visible to the last image where the muscle was visible. Quadriceps MV was calculated by the sum of RF, VM and VLI, and hamstrings MV by the sum of BFlh, BFsh, ST and SM. MV results are from the dominant leg (chosen as the front leg in the starting sprint position). The intra-class correlation coefficients of variation for the intra-rater agreement of the volumetric values were 1.00 ± 0.05 and 0.57% ± 0.42% for the different muscles assessed; similar to previous estimations of error using this method.[93]

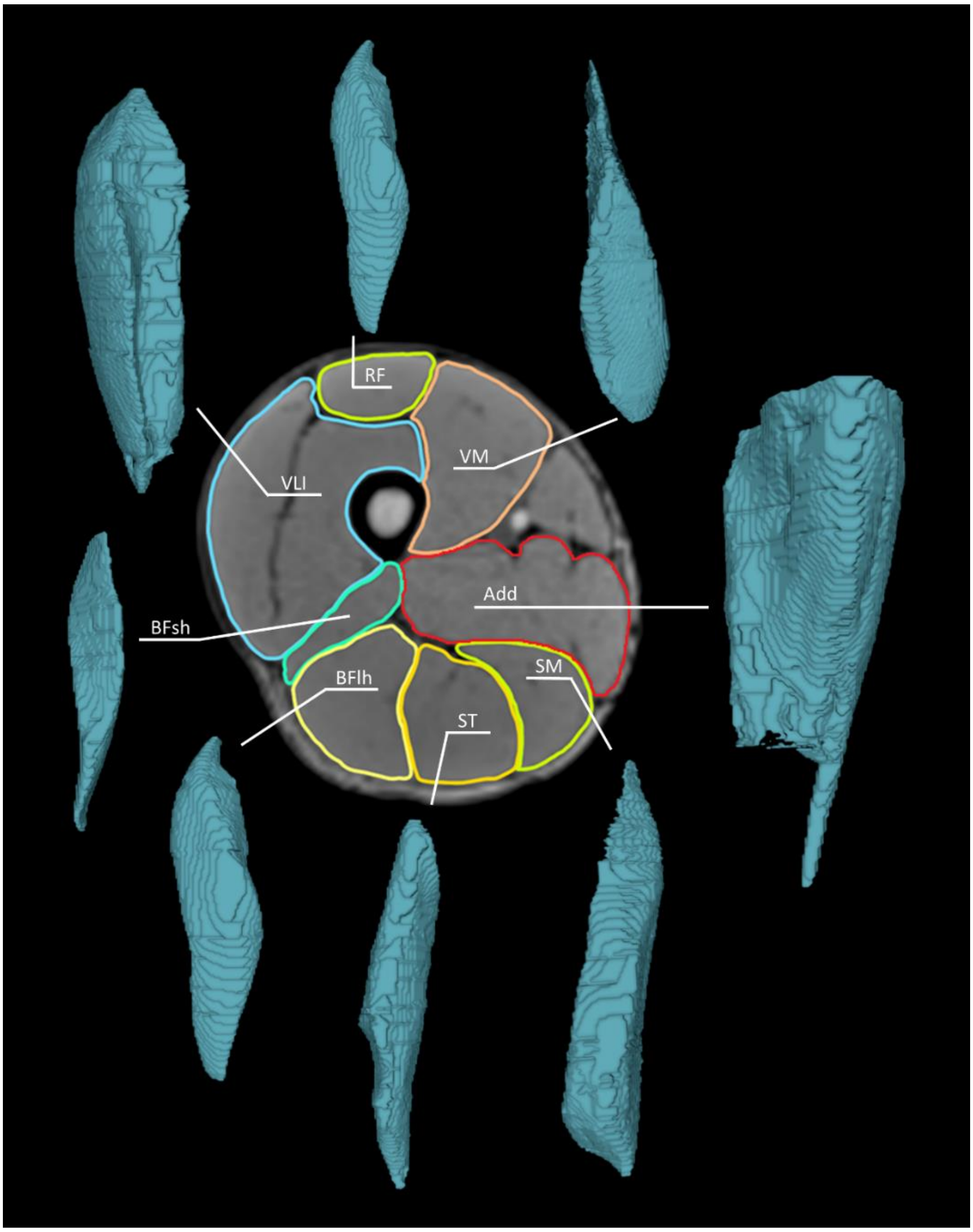

Figure 4.1.2 Muscle volumes reconstruction from Study I.

Manually outlined cross-sectional muscle area edges on a single cross-sectional image at 50% of the femur length of a representative sprinter (nº3), with their respective tridimensional reconstructions. RF, Rectus femoris. VLI, Vastus lateralis + Vastus intermedius. VM, Vastus medialis. BFlh, Biceps femoris long head. BFsh, Biceps femoris short head. ST, Semitendinosus. SM, Semimembranosus. Add, Adductor muscle group.

Statistical analyses

Normal distribution of data was checked using the Shapiro-Wilk test. An independent sample T-test was performed to compare the different variables between sprinters and actives. ESs (Cohen's d) and 90% confidence intervals (lower limit : upper limit) were calculated to assess the difference between 2 group means. Thresholds for ES values were: 0.2, trivial; 0.6, small; 1.2, moderate; 2.0, large; 4.0, very large; and > 4.0, extremely large.[94] Pearson correlation coefficient was employed to evaluate the association between the variables of interest, with thresholds being: 0.40-0.59, moderate; 0.60-0.79, strong; 0.80-1, very strong. Data are presented as mean ± SD. Statistical significance was set at $P < 0.05$. Statistical analysis was performed using SPSS v.23.0.0.0 (IBM, Armonk, New York).

4.1.4 Results

Anthropometric characteristics

Sprinters and actives showed no significant differences in physical and anthropometric characteristics (Table 4.1.1). Due to similar body height, mass, fat and length of the segments in both groups, there was no need to normalise variables and further analyses of MVs were performed with absolute values.

	Actives (n=9)	**Sprinters** (n=7)
Age (years)	24.34 ± 4.25	24.07 ± 2.81
Height (m)	1.78 ± 0.07	1.80 ± 0.07
Mass (kg)	74.41 ± 4.61	74.19 ± 8.01
Body mass index	23.24 ± 2.23	22.92 ± 1.02
Fat percentage (%)	11.44 ± 1.74	9.57 ± 1.99
Leg length (m)	0.88 ± 0.03	0.89 ± 0.05
Thigh length (m)	0.48 ± 0.02	0.49 ± 0.02
Shank length (m)	0.40 ± 0.01	0.40 ± 0.03
Ratio leg length/height	0.49 ± 0.01	0.50 ± 0.01

Table 4.1.1 Characteristics of participants from Study I.

Physical and anthropometric characteristics of participants from Study I. Data are means ± standard deviations. Note that no statistical differences were found between groups.

Sprint mechanical properties and performance

Regarding the SMPs, sprinters showed significantly higher V_0 (20%, ES = 4.53, $P < 0.001$) and P_{max} (28%, ES = 3.04, $P < 0.001$). F_0 showed no significant differences between groups ($P = 0.135$), although was moderately greater in sprinters (ES = 0.80). Concerning sprint performance, sprinters were faster over both distances; 10 m (7%, ES = 2.12, $P < 0.001$) and 40 m (11%, ES = 3.68, $P < 0.001$) (Table 4.1.2).

Muscle Volumes

Sprinters showed significantly higher quadriceps MV (14%, ES = 1.12, $P < 0.05$), adductors MV (23%, ES = 1.33, $P < 0.05$) and hamstrings MV (32%, ES = 2.11, $P < 0.01$) than actives. Specifically, sprinters had significantly larger RF (26%, $P < 0.05$, ES = 1.08), BFlh (25%, $P < 0.01$, ES = 1.85), ST (35%, $P < 0.01$, ES =

1.83) and SM (37 $P < 0.01$, ES = 2.31). No statistical differences were found in VM (18%, $P = .116$, ES = 0.92), VEI (11%, $P = .74$, ES = 0.97) or BFsh (25%, $P = .104$, ES = 0.96), although moderate ES was found in each of these three muscles (Table 4.1.2).

	Actives (n=9)	**Sprinters** (n=7)	**ES (CI)**
Muscle volumes			
Rectus femoris (cm^3)	256.9 ± 39.7	322.7 ± 81.2*	1.08 (0.19 : 1.96)
Vastus medialis (cm^3)	494.3 ± 103.3	584.8 ± 92.8	0.92 (0.04 : 1.79)
Vastus lateralis + intermedius (cm^3)	1324.8 ± 107.6	1467.3 ± 185.6	0.97 (0.09 : 1.85)
Biceps femoris long head (cm^3)	234.9 ± 21.0	294.4 ± 42.7**	1.85 (0.86 : 2.84)
Biceps femoris short head (cm^3)	114.3 ± 22.6	143.7 ± 38.6	0.96 (0.09 : 1.84)
Semitendinosus (cm^3)	254.7 ± 36.9	344.0 ± 61.4**	1.83 (0.84 : 2.81)
Semimembranosus (cm^3)	261.0 ± 33.3	358.3 ± 51.6**	2.31 (1.24 : 3.38)
Quadriceps (cm^3)	2076.0 ± 212.4	2374.7 ± 326.8*	1.12 (0.23 : 2.01)
Hamstrings (cm^3)	865.0 ± 85.0	1140.5 ± 173.3**	2.11 (1.08 : 3.15)
Adductors (cm^3)	1115.1 ± 96.5	1376.7 ± 278.1*	1.33 (0.42 : 2.25)
Sprint mechanical properties and performance			
F_0 ($N.kg^{-1}$)	7.94 ± 0.55	8.50 ± 0.86	0.80 (-0.06 : 1.66)
V_0 ($m.s^{-1}$)	8.50 ± 0.38	10.22 ± 0.38**	4.53 (2.97 : 6.08)
P_{max} ($W.kg^{-1}$)	16.87 ± 1.19	21.70 ± 2.00**	3.04 (1.83 : 4.25)
10 m (s)	2.11 ± 0.07	1.97 ± 0.06**	-2.12 (-3.16 : -1.09)
40 m (s)	5.90 ± 0.22	5.25 ± 0.09**	-3.68 (-5.04 : -2.33)

Table 4.1.2 Variables measured from Study I.

*F_0, theoretical maximal horizontal force. V_0, theoretical maximal horizontal velocity. P_{max}, maximal horizontal power. 10 m, time achieved in 10 m sprint; 40 m time achieved in 40 m sprint. Data are means ± standard deviation or effect size (ES) ± 90% confidence interval (CI). * Significant difference between groups at* P *< 0.05. ** Significant difference between groups at $P < 0.01$.*

Correlation analysis

Hamstrings MV correlated strongly with V_0 (r = 0.757, $P < 0.01$), and moderately with P_{max} (r = 0.559, $P < 0.05$). Hamstrings MV also showed a strong correlation with 40 m sprint time (r = -0.670, $P < 0.01$) and, albeit not significant, moderate with 10 m sprint time (r = -0.463, $P = 0.071$) (Figure 4.1.3). MV of adductors was found to correlate strongly with V_0 (r = 0.642), and moderately with 40 m sprint time (r = -0.563, $P < 0.05$).

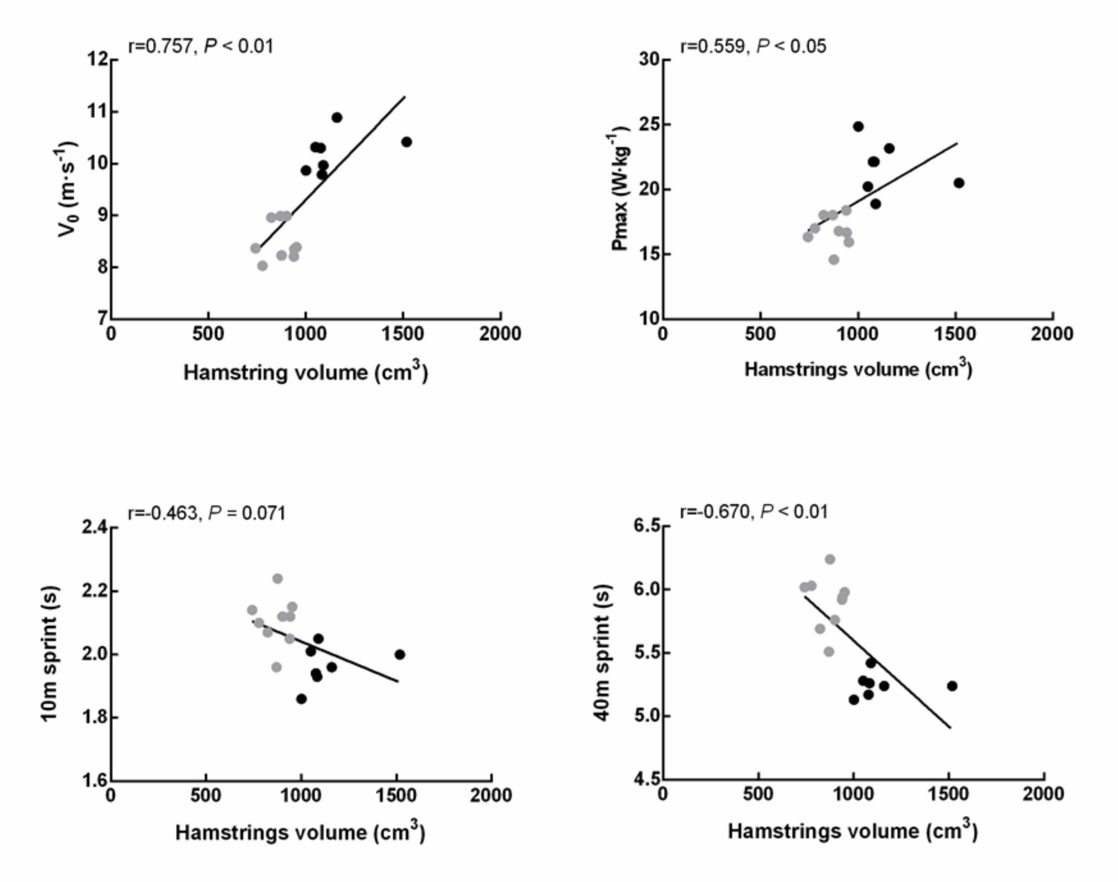

Figure 4.1.3 Correlation analysis from Study I.

Association between hamstrings muscle volume and the different sprint mechanical and performance variables.

r, Pearson's correlation coefficient. Grey circles, actives. Black circles, sprinters. Correlation analysis was performed with pooled data (n=16).

4.1.5 Discussion

This study examined the sprint mechanical properties and performance, and thigh MVs of physically active males and high-level sprinters, and the relationship between these variables. The main findings were: 1) sprinters exhibited greater mechanical properties and were significantly faster; 2) larger MVs were found in sprinters' thighs, especially in hamstrings, and 3) strong correlations were found between hamstring MV and SMPs and performance.

The P-F-V relationship offers an insight into the limits of the human body for sprint performance. Sprinters presented very large (ES = 3.04) and extremely large (ES = 4.53) differences in P_{max} and V_0, respectively, compared to actives. Sprinters also presented moderately higher levels of F_0 despite no statistical differences being found, most likely due to variability of the sample. Similarly, Morin and colleagues[11] reported high differences in V_0 and P_{max}, and no differences in F_0, when comparing top-level sprinters with recreational athletes. V_0 represents the theoretical maximal velocity and also reflects the ability to produce higher horizontal GRFs at high speeds which, ultimately, allows the athlete to reach faster top speeds.[11,18,24] In fact, our results support the notion that V_0 or velocity-oriented profile is the determinant for sprinters, and the differential factor between recreational and high-level athletes.[11] Power output has been suggested as one of the predicting factors of sprint performance.[24,99] Historically, P_{max} has been measured during lifting, jumping or cycling, due to safeness, ease and reliability, and then related to sprint performance, showing high correlations and presenting as a determinant of sprint performance.[96,100,101] Moreover, when P_{max} is measured during sprinting and then related to sprint performance it seems to show even stronger correlations.[11,18,24,99] In a recent study, Colyer et al.[102] showed that sprinters continue accelerating beyond the soccer players' velocity plateau due to the much higher horizontal power produced by the sprinters. In this regard, we found nearly perfect correlations between P_{max} and sprint performance over 10 m ($r = -0.937$, $P < 0.001$) and 40 m ($r = -0.913$, $P < 0.001$).

As expected, sprinters were much faster than actives, although the magnitude of the difference increased with the sprint distance: 7% over 10 m (ES = 2.12), 11%

over 40 m (ES = 3.68). Additionally, it can be speculated that these differences would be even greater with longer distances (i.e., 80 m or 100 m) due to the differences found in V_0. Although sprinters accelerated faster than actives, a greater difference between cohorts was found at top end speeds. This is to be expected given that the sprinters were specialists in the 100 m event, and the actives were accustomed to sprinting over short distances. The sprinter's P-F-V profile found here, characterised by higher horizontal forces and power produced at faster speeds, might be related to intrinsic neuromuscular properties (fast-twitch fibres, increased neural drive, and stiffer musculotendon properties), but also to the technical ability to orient the GRFs forward during sprinting.[24,76] It is well known that this ability is the strongest predictor of acceleration and sprint performance.[10,11,18,24]

Performance in sprinting is achieved by producing high forces at fast contraction speeds, resulting in greater power output production through the prime mover muscles.[42,43,46] While there may be a genetic component to the muscle size profiles observed here, it is likely that training effects also contribute to the observed differences, reflecting the role of each muscle group in sprinting. In this regard, we found greater thigh MVs in sprinters, although not all muscles analysed were proportionally larger. Hamstrings, adductors and quadriceps MVs were, respectively, 32% (ES = 2.11, $P < 0.01$), 23% (ES = 1.33, $P < 0.05$) and 14% (ES = 1.12, $P < 0.05$) higher in sprinters than actives (Table 4.1.2).

Concerning individual hamstring muscles differences, we found far larger MVs in sprinters compared with actives (Table 4.1.2). These differences are in line with the results presented by Handsfield et al.[42] who also found 32% larger hamstring muscles compared with healthy actives individuals. Along similar lines, Bex et al.[43] reported 17% larger hamstrings in sprinters compared with endurance runners, supporting the idea that sprinters have disproportionally greater hamstrings. In this regard, Hoshikawa et al.[41] compared thigh muscle CSAs in different athletic populations, finding that sprinters have larger hamstrings than other groups. It is well documented that hamstrings are key muscles in sprinting, showing peak activity from the mid swing until terminal stance.[42,69,70,72,75] The bi-articular hamstring muscles have been shown to contribute to a net transfer of power from proximal to distal joints,[103] pulling the body over the stance leg with minimal loss of horizontal speed and, therefore, making a significant contribution to propulsion.[72,75,76] Interestingly, we found significantly larger volume in all bi-articular hamstring muscles; BFlh, ST and SM, but no statistical differences with the only mono-articular hamstring, BFsh (Table 4.1.2), supporting the relevance of these specific muscles in sprinting. Moreover, in a recent study, Ema et al.[47] found that sprinters had significantly greater MV of the BFlh, ST and SM, and no differences in BFsh, compared with untrained males.

Sprinters also showed larger adductor muscles compared with actives (Table 4.1.2). Our results are also in agreement with Handsfield et al.[42] who found larger adductor muscles comparing sprinters with non-sprinters. Similarly to our study, Ema et al.[47] compared the thigh MVs of a group of sprinters and a group of physically and age-matched untrained males and also found that sprinters had significantly greater adductors. Adductors are, in fact, an important muscle group during sprinting, as described in the literature.[48,49,70,71] Adductor magnus is an important hip extensor, and the rest of adductors included in the group (adductor longus, adductor brevis, adductor minimus, pectineus and gracilis) act as hip flexors.[79–81] During the late swing until the terminal stance adductor magnus remains active, contributing to the hip extension,[70,71] meanwhile, during the early and mid swing the other adductors assist the hip flexion.[70]

As previously mentioned, quadriceps were larger in sprinters than in actives, despite not being relatively as large as hamstrings. Interestingly, higher differences were found in RF compared with the vastus muscles (Table 4.1.2). RF is the only bi-articular quadriceps, contributing to the knee extension and hip flexion. During sprinting, the vastus muscles are active during the support phase. In contrast, RF is active during the whole support phase until the mid swing, due to this dual role.[6,69,75,103] Using computational modelling of muscles, Dorn et al.[69] predicted large implications of RF rather than vastus muscles in high speed running. Hip flexors are, in fact, key muscles in sprinting, driving the leg forward during the swing phase, and their size is related to sprint performance, being one of the differential factors of the sprinters.[42,47,69] In this regard, our results are in accordance with Ema et al.[47] who found differences in RF but not in the vastus muscles, when comparing sprinters with untrained males. Many studies have highlighted the importance of the muscularity of the quadriceps in sprinting[42–44] despite a lack of certainty about its real contribution. We believe that this is because quadriceps is a historically over-studied and over-trained muscle. When focusing only on quadriceps, and not on surrounding muscles, it is easy to find these relationships. Sprinters' training often includes weightlifting exercises (i.e., cleans, squats, lunges) which could promote hypertrophy of the vastus muscles but does not reflect the specific demands of sprinting.

Moderate to strong correlations were found between hamstrings MV and SMPs and performance (Figure 4.1.3), confirming the role of this muscle group in sprinting, as previously proposed.[43,72,75] There was a clear tendency for the associations between hamstrings MV and sprint variables to strengthen as the distance increased. In 10 m sprint performance, hamstrings MV showed a tendency towards moderate association (r = -0.463, $P = 0.071$), while in 40 m we found a strong correlation (r = -0.670, $P < 0.01$), and in V_0 the association was even stronger (r = 0.757, $P < 0.01$). A possible contributor to these outcomes could be that during the first steps of a sprint, the body leans forward, positioning the athlete's CM ahead of the base of support and assisting the acceleration. Additionally, speed development during the first steps depends mainly on the powerful extension of all major lower extremity joints, increasing the participation of the quadriceps.[70,77] In contrast, during maximum velocity speeds, runners adopt an upright posture, and intense backward movements of the lower limb are necessary during both stance and late swing, with the hamstring muscles producing very high forces in both phases.[69,72,75] P_{max}, as an indicator of sprint performance, also showed a moderate association with hamstrings MV (r = 0.559, $P < 0.05$).

Adductors MV showed strong correlations with V_0 (r = 0.642, $P < 0.01$) and moderate with 40 m sprint performance (r = -0.563, $P < 0.05$). These results suggest that the muscularity of adductors might also be related to sprint performance, but to a smaller extent than hamstrings muscularity. In fact, the level of association showed by adductors MV is weaker than that presented by hamstrings and with fewer variables. Adductors muscularity has already been proposed as a determinant of sprint performance.[48,49] Tottori et al.[49] studied the relationship between adductors and sprint performance in pre-adolescent sprinters, showing that larger adductors were related to lower sprint times. These results cannot be directly compared to our findings due to the age-related differences in the subjects analysed, however, there might be some similarities. Additionally, Sugisaki et al.[48] investigated the relationship between 30 m sprint time and some lower limb muscle CSAs in a group of sprinters and middle distance runners, and concluded that having greater hip adductor muscles is advantageous for achieving higher sprint performance. However, in a recent study, the same author analysed the association of all lower limb muscles with sprint performance in sprinters, finding moderate association between hamstrings MV and 100 m sprint time, and an absence of correlation between adductors MV and sprint performance.[46] Taking all this together, we conclude that adductors MV plays some role in determining sprint performance, however, to a lesser degree than hamstrings MV.

4.1.6 Conclusions

From the findings in this study it can be concluded that sprinters were significantly faster and exhibited greater SMP compared to trained males. Moreover, larger MVs were found in sprinters' thighs, especially in the hamstring musculature. Finally, strong correlations were found between hamstrings MV, SMPs and sprint performance. This study adds to the literature regarding the anthropometrical factors of sprinters, especially the importance of the hamstring musculature. Moreover, findings highlight that V_0 and the ability to produce higher horizontal GRFs at higher speeds are crucial in sprinters and enable athletes to reach higher maximum velocities.

4.2 Study II

Male vs. female sprinters.

4.2.1 Abstract

The purpose of this study was to determine and compare thigh MVs, and SMPs and performance between male and female national-level sprinters. We also studied possible relationships between thigh MVs and sprint performance. Nine male and eight female national-level sprinters participated in the study. T1-weighted MRI of the thighs were obtained to determine MVs of quadriceps, hamstrings and adductors. Sprint performance was measured as the time to cover 40 and 80 m. Instantaneous sprint velocity was measured by radar to obtain F_0, V_0 and P_{max}. When MVs were normalized by height-mass, males showed larger hamstrings (14%, ES = 1.26, $P < 0.05$), while quadriceps and adductors showed no statistically significant differences. Males were extremely faster than females over both distances: 40 m (14%, ES = 6.68, $P < 0.001$) and 80 m (15%, ES = 5.01, $P < 0.001$). Males also showed increased SMPs, with larger F_0 (19%, ES = 1.98, $P < 0.01$), much larger P_{max} (46%, ES = 3.76, $P < 0.001$), and extremely larger V_0 (23%, ES = 6.97, $P < 0.001$). Hamstrings and adductors MVs correlated strongly (r = -0.685, $P < 0.01$) and moderately (r = -0.530, $P < 0.05$), respectively, with sprint performance; while quadriceps showed no association. Males were faster than females and showed larger MVs, especially in hamstrings. Moreover, hamstrings MV showed strong associations with sprint performance as previously proposed.

Keywords: *muscle volume, hamstrings, adductors, sprint performance*

4.2.2 Introduction

Sprint ability is one of the most highly appreciated individual qualities in a majority of sports. Many factors seem to influence sprint performance; however, it is believed that the ability to produce large propulsive forces is one of its strongest predictors.[10,11,24] The overall mechanical capacity to apply anteroposterior GRFs when sprinting is portrayed by the linear F-V and parabolic P-V relationships, which characterize the mechanical limits of the entire neuromuscular system.[18,24] In this regard, the P-F-V profile can be accurately computed from anthropometric (body mass and stature) and spatiotemporal (split times or instantaneous velocity) variables, using a validated computerised method.[24]

To move the body forward when running humans have to produce a combination of lower limb joint torques. MV is the major determinant of joint torque;[37] hence, identifying the key lower limb muscles in sprinting is important for coaches and athletes. To date, many studies have investigated the relationship between lower-limb muscularity and sprint performance, leading to some controversy concerning the results.[46–50] Some authors who have studied quadriceps have found positive relationships between the degree of muscularity and sprint performance.[48,49] Nevertheless, Miyake et al.[50] observed that knee extensor moment arm, and not quadriceps CSA, correlate with sprint performance. Moreover, Sugisaki et al.[48] and Tottori et al.[49] concluded that having greater adductor muscles is advantageous for sprint performance. In contrast to those results, in a recent work, Sugisaki et al.[46] found relationships between sprint performance and both hamstrings and glutes, but no association with quadriceps or adductors. Along the same lines, after comparing sprinters to non-sprinters, Ema et al.[47] found that sprinters have larger hamstrings and adductors, but that there was no difference in quadriceps. Moreover, that study reported strong correlations between hamstrings and sprint performance. However, the vast majority of studies analysing MVs in sprinters have been performed on males, and it seems there is a lack of muscularity studies in female sprinters.

A substantial gender difference in sprint performance is a common observation, regardless of the level: males are faster than females.[104–106] It is believed that most performance differences are due to variations in morphological and physiological characteristics typical of men and women.[104] Success in sprint is highly dependent on the generation of large forces over short periods of time;[12,96,105,107] thus, power production is believed to be a strong determinant of sprint performance.[11,18,24,96] In this regard, women tend to have a lower absolute muscle mass and smaller skeletons.[1,105] During sprinting, these anthropometric disparities could lead to differences in the capacity to produce large forward acceleration in order to achieve maximal speed.[1] Hence, differences in MVs between male and female sprinters, and the relation between MV and performance are potentially a highly fertile field of investigation.

Therefore, the purpose of this study was to determine and compare thigh MVs, and SMPs and performance between male and female national-level sprinters. Additionally, the relationships between thigh MVs and sprint performance were investigated.

4.2.3 Methods

Participants

Nine male (age 23.3 ± 1.7 years; body mass 73.8 ± 8.6 kg; height 180.0 ± 7.3 cm) and eight female (age 23.9 ± 5.3 years; body mass 57.0 ± 6.9 kg; height 163.3 ± 7.9 cm) national-level sprinters participated in this study. They were specialists at sprinting from 100 m to 400 m, and they had performed competitive sprinting for at least 4 years. The sprinters were classified based on their personal best performance according to the International Amateur Athletic Federation (IAAF) scoring system. This IAAF classification allows intra- and inter-individual comparison of performance, regardless of event and/or sex. Eight skinfold thicknesses were measured to estimate the percentage of body fat using the equations published by Withers et al.[98] All the measurements in the present study were obtained during the off-season. All the participants gave informed written consent to participate in the study, which was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of the Catalan Sports Council (Generalitat of Catalonia) (0099S/690/2013).

Design

A cross-sectional study was designed to investigate differences in sprint performance, thigh MVs and SMPs between male and female national-level sprinters, and examine possible relationships between these factors. All the testing occurred at the beginning of the pre-season, when no physical or performance adaptations occurred. MRI analysis were performed after at least 72 h of rest, to avoid any influence of acute muscle swelling.[92] Meanwhile, sprint tests were conducted after at least 48 h of rest. All the sprint tests were performed over a tartan surface of a track in a stadium. The 40 m sprint and SMPs tests were recorded during the same sprint. In all the sprint tests, the athletes adopted the three-point start position, using sprint spikes. Moreover, in order to achieve a faster and more reliable start, they were told to start at will, when they wanted.

Muscle volumes

A series of cross-sectional images of each subject’s thighs were obtained by MRI with an Avanto 1.5T (Magnetom Avanto, Siemens Healthineers, Germany). Transaxial images (slice thickness, 2 mm; increment, 2 mm) were acquired in a 320x320 matrix, 40x40 field of view in 20-second blocks. The volunteers were placed supine inside the scanner with their heads outside the MR bore, with their thighs covered with a leg coil, while their limb position was fixed through the use of a custom-made foot restraint. Between 280 and 320 images (depending on each subject’s thigh length) were obtained for each leg from the iliac spine to the patella.

VL, VI, VM and RF were outlined together and identified as quadriceps. BFlh, BFsh, ST and SM were outlined together and identified as hamstrings. The same approach was adopted for the assessment of adductors MV, which includes adductor magnus, adductor longus, adductor brevis, adductor minimus, pectineus and gracilis. The edges of the quadriceps, hamstrings and adductors were manually outlined, image by image, and by the same researcher, following the reference method proposed by Nordez et al.,[53] using Osirix 8.5.2 (Pixmeo, Geneva, Switzerland). The total volume of each muscle was calculated from the range between the last image where the ischial tuberosity was visible and the last image where the muscle was visible (Figure 4.2.1). MV results are shown as the average of right and left thighs. The intra-investigator coefficient of variation for muscle segmentation was 1.1% ± 0.4% for the muscles assessed, similar to previous estimations of error for this method.[53,93]

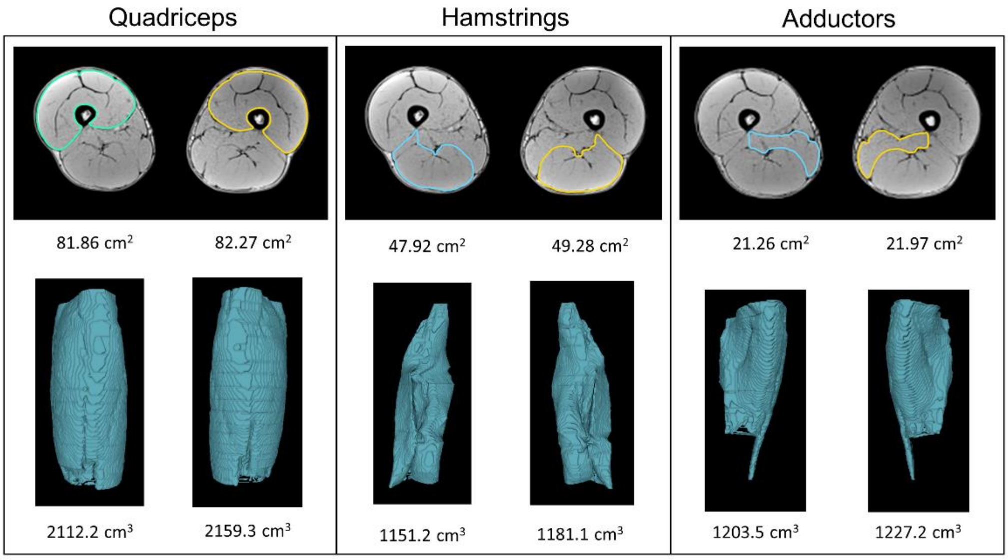

Figure 4.2.1 Muscle volume reconstructions from study II.

Representative magnetic resonance imaging scans, at mid-thigh, of subject nº 10 (male) used for measuring cross-sectional area of quadriceps, hamstrings and adductors and their respective muscle volumes reconstructions.

To reduce the effects of body size on muscle size differences between males and females, MVs were normalized by body size metrics. Lower-limb MVs have been shown to vary with the product of height and body mass in healthy active subjects.[42,45] Thus, MVs were normalized by height-mass.

Sprint performance

Sprint tests were carried out on two different days, separated by 48 h. On day one, sprinters performed two maximal 40 m sprints with 6 min of rest between them; and on day two, they performed two maximal 80 m sprints with 15 min of rest. After 40 min of standardized warm-up and activation conducted by their coach, the athletes started the tests. Two pairs of Microgate Witty photocells (Microgate, Italy) were placed at distances of 0 and 40 m, and at 0 and 80 m, for the 40 m and 80 m sprint, respectively. The best time over each distance was used for further analysis. The sprinters started their attempts just before the first photocell, to start the timer with their very first movement.

Sprint mechanical properties

Instantaneous velocity over the 40 m sprint was measured by radar (Stalker ATSII, Plano, Texas, USA) with a sampling rate of 48 Hz, as previously validated in human sprint experiments [24]. The device was placed on a tripod 2 m behind the subject at a height of 1 m: approximately the average subject's CM. Subjects were instructed to hold their three-point starting position static for about one second, and then to start running forward without any countermovement. As mentioned, the fastest trial, based on the photocell times, was selected for further analysis. The resultant data were subsequently analyzed using the simple field method validated by Samozino et al.[24] Briefly, this computation method is based on macroscopic inverse dynamics analysis of the CM motion. Velocity-time data are fitted to an exponential function, after which instantaneous velocity is derived to compute the net anteroposterior GRF and power. Individual F-V relationships are then extrapolated to calculate F_0 and V_0 capabilities, and the underlying P_{max}, as described elsewhere.[1,11,18,24]

Statistical analysis

Descriptive data are presented as mean ± SD. The normal distribution of the data was checked using the Shapiro-Wilk tests. An independent sample t-test was performed to compare the different variables between male and female sprinters. ESs (Cohen's d) and 90% CI (lower limit : upper limit) were calculated to assess the difference between the means of the two groups. The thresholds for ES values were: 0.2, trivial; 0.6, small; 1.2, moderate; 2.0, large; 4.0, very large; and > 4.0, extremely large.[94] The Pearson correlation coefficient was employed to evaluate the association between the variables of interest of the pooled data, with thresholds of: 0.40-0.59, moderate; 0.60-0.79, strong; 0.80-1, very strong. The significance level was set at $P < 0.05$. Statistical analysis was performed using SPSS v.23.0.0.0 (IBM, Armonk, New York).

4.2.4 Results

Physical characteristics

Male and female sprinters were similar in age and body mass index. However, they presented significant differences in anthropometric characteristics such as height, mass and percentage of fat. They also differed in terms of IAAF performance scores (Table 4.2.1).

	Females (n=8)	**Males** (n=9)
Age (years)	23.9 ± 5.3	23.3 ± 1.7
Height (m)	1.63 ± 0.08	1.80 ± 0.07**
Mass (kg)	57.0 ± 6.9	73.8 ± 8.6**
Body mass index	21.4 ± 1.4	22.6 ± 1.3
Fat percentage (%)	14.9 ± 2.9	9.2 ± 1.0**
Running performance (IAAF score)	912 ± 40	990 ± 70*

Table 4.2.1 Characteristics of participants from study II.

Physical and performance characteristics of participants from study II. IAAF, International Amateur Athletic Federation. Data are means ± standard deviation.
** Significant differences between groups at P < 0.05. ** Significant differences between groups at P < 0.01.*

Muscle volumes

Due to differences in body size (Table 4.2.1) absolute MVs of the thigh were significantly higher in males than in females (58%-64%, ES = 2.75-3.88, $P < 0.001$) (Table 4.2.2). However, when normalized by height-mass, males showed larger hamstrings (14%, ES = 1.26, $P < 0.05$), while quadriceps and adductors showed no statistical difference, although ESs for men were moderately higher (ES = 0.86 and ES = 0.83, respectively) (Table 4.2.2 and Figure 4.2.2).

	Females (n=8)	**Males** (n=9)	**ES (CI)**
Absolute muscle volumes			
Quadriceps (cm^3)	1461 ± 238	2309 ± 200**	3.88 (2.53 : 5.24)
Hamstrings (cm^3)	688 ± 98	1125 ± 151**	3.39 (2.14 : 4.63)
Adductors (cm^3)	803 ± 140	1268 ± 191**	2.75 (1.64 : 3.86)
Normalised muscle volumes			
Quadriceps (cm^3·kg^{-1}·m^{-1})	15.74 ± 2.20	17.44 ± 1.78	0.86 (0.02 : 1.69)
Hamstrings (cm^3·kg^{-1}·m^{-1})	7.44 ± 1.01	8.45 ± 0.56*	1.26 (0.39 : 2.13)
Adductors (cm^3·kg^{-1}·m^{-1})	8.66 ± 1.20	9.51 ± 0.85	0.83 (-0.01 : 1.66)
Sprint performance			
40 m (s)	6.12 ± 0.15	5.25 ± 0.11**	-6.68 (-8.73 : -4.63)
80 m (s)	11.07 ± 0.39	9.43 ± 0.26**	-5.01 (-6.64 : -3.39)
Sprint mechanical properties			
F_0 (N.kg^{-1})	7.42 ± 0.38	8.82 ± 0.90**	1.98 (1.01: 2.96)
V_0 (m.s^{-1})	7.91 ± 0.26	9.76 ± 0.27**	6.97 (4.85 : 9.09)
P_{max} (W.kg^{-1})	14.67 ± 1.06	21.52 ± 2.29**	3.76 (2.43 : 5.09)

Table 4.2.2 Variables measured from study II.

*F0, theoretical maximal horizontal force. V0, theoretical maximal horizontal velocity. Pmax, theoretical maximal horizontal power. 10m, time achieved in 10m sprint, 40m time achieved in 40m sprint. Data are means ± standard deviation or effect size (ES) ± 90% confidence interval (CI). * Significant difference between groups at P < 0.05. ** Significant difference between groups at P < 0.01.*

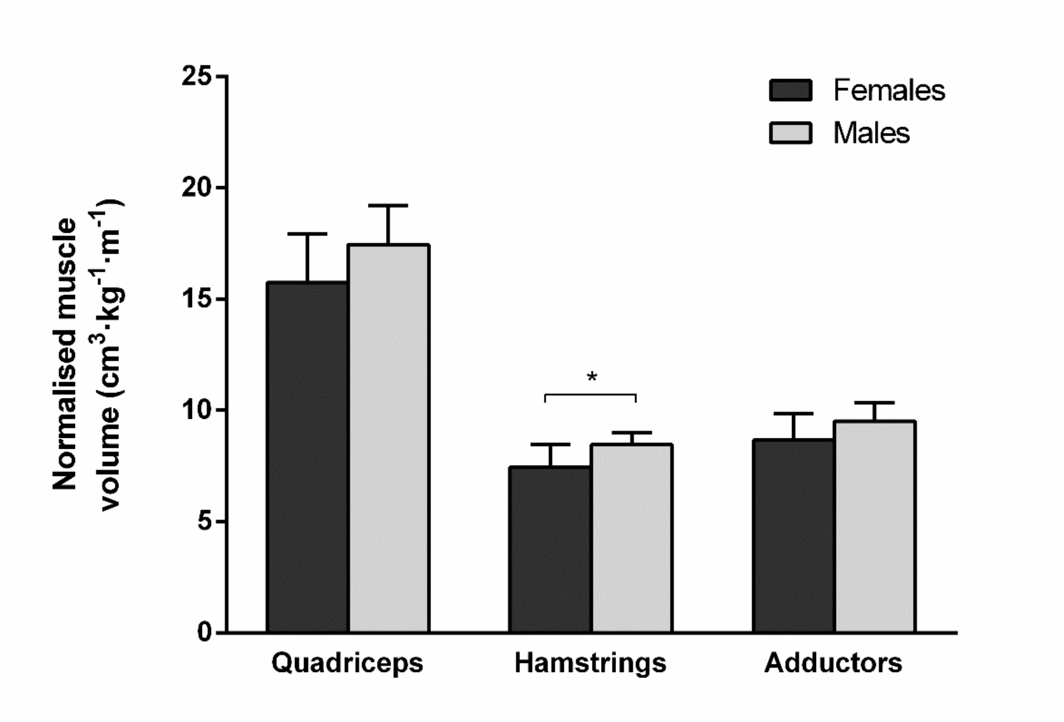

Figure 4.2.2 Absolute muscle volumes from study II.

*Normalised muscle volumes of male and female sprinters. * Significant difference between groups at P < 0.05.*

Sprint performance

Regarding sprint performance, males were much faster than females over both distances, with extremely large ESs: 40 m (14%, ES = 6.68, $P < 0.001$), 80 m (15%, ES = 5.01, $P < 0.001$) (Table 4.2.2).

Sprint mechanical properties

Males also showed increased SMPs, with a larger F_0 (19%, ES = 1.98, $P < 0.01$), much larger P_{max} (46%, ES = 3.76, $P < 0.001$), and very much larger V_0 (23%, ES = 6.97, $P < 0.001$) (Table 4.2.2 and Figure 4.2.3).

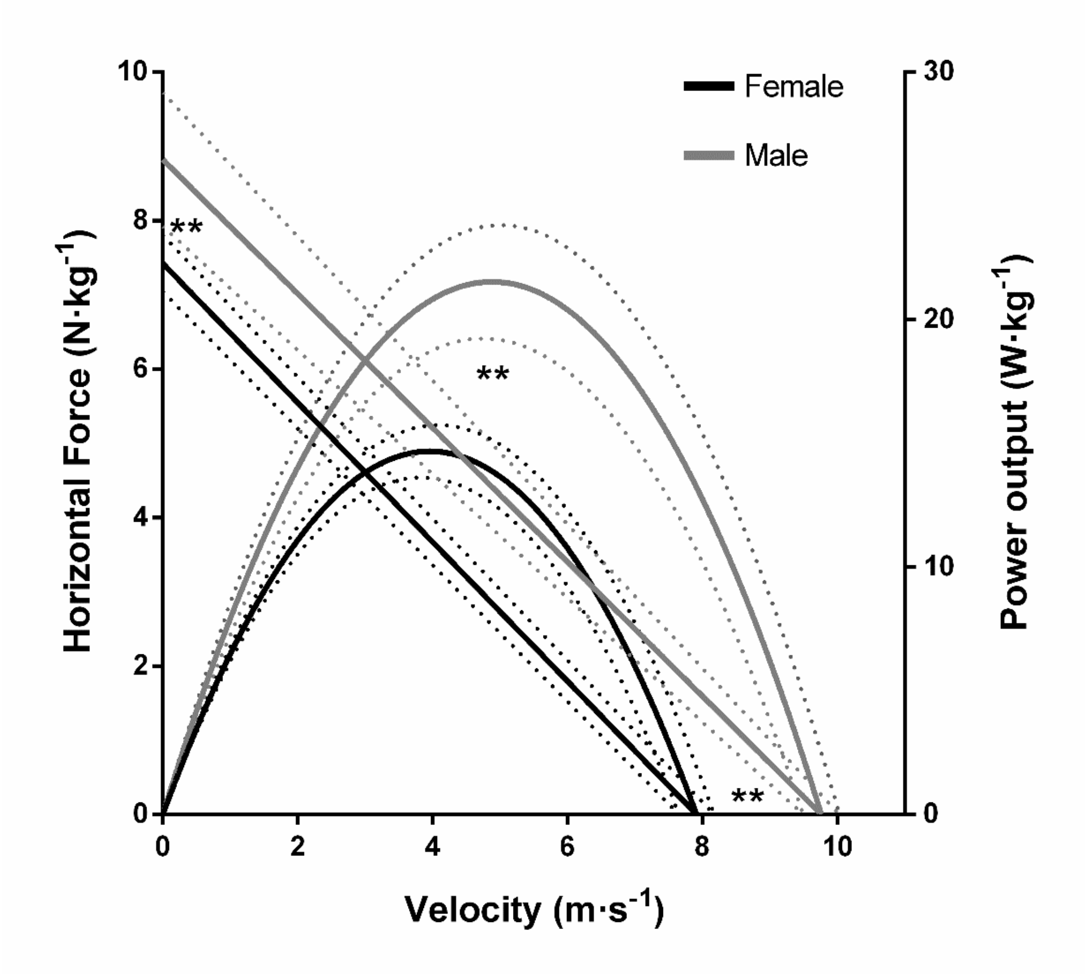

Figure 4.2.3 Power-force-velocity profiles from study II.

*Females (black lines) and males (grey lines) power-force-velocity profiles and sprint mechanical properties. Bold lines represent averaged data. Dotted lines represent standard deviations. ** Significant difference between groups at $P < 0.01$ in F_0, V_0 and P_{max}.*

Correlation analysis

Normalized hamstrings MV correlated strongly with 40 m sprint time (r = -0.647, $P < 0.01$), 80 m sprint time (r = -0.685, $P < 0.01$) and V_0 (r = 0.646, $P < 0.01$); and moderately with P_{max} (r = 0.568, $P < 0.05$). No correlation was found between normalized hamstrings MV and F_0 (Figure 4.2.4).

Normalized adductors MV correlated moderately with 40 m sprint time (r = -0.514, $P < 0.05$), 80 m sprint time (r = -0.530, $P < 0.05$), F_0 (r = 0.503, $P < 0.05$) and P_{max} (r = 0.499, $P < 0.05$). No correlation was found between normalized adductors MV and V_0 (Figure 4.2.4).

No correlations were found between normalized quadriceps MV and any sprint performance or mechanical properties variable.

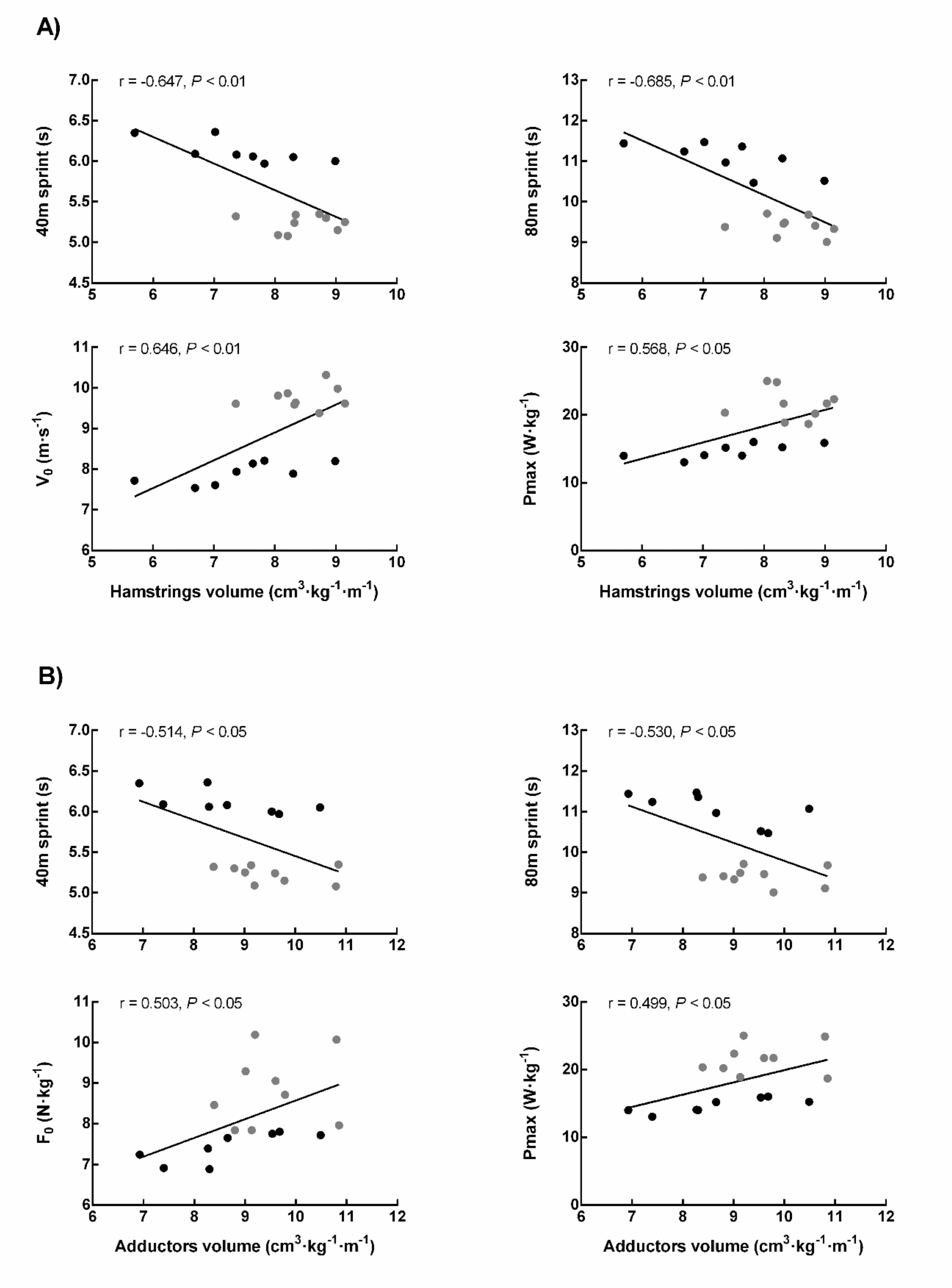

Figure 4.2.4 Correlation analysis from study II.

Association between (A) hamstrings and (B) adductors muscle volume and sprint performance and mechanical properties.

r, Pearson's correlation coefficient. V_0, theoretical maximal velocity. P_{max}, maximal power output. F_0, theoretical maximal anterior-posterior force. Black circles represent female sprinters. Grey circles represent male sprinters.

Correlation analysis was performed with pooled data (n=17).

4.2.5 Discussion

In the present study, we analysed thigh MVs, SMPs and performance of male and female sprinters; and also the relationship between thigh MVs and sprint performance. The main findings were; 1) males showed larger hamstrings MV, while quadriceps and adductors showed no differences, 2) males were very much faster than females and exhibited greater SMPs, especially maximal velocity, and 3) strong correlations were found between hamstrings MV and sprint performance, and moderate correlations between adductors MV and sprint performance.

Males had very large thigh MVs compared with females (Table 4.2.2). MV has been shown to be related to the length of the segment and the mass of the muscle,[42,45] and sizes of the segments are directly related to total size and mass of the human body.[45] In this regard, the two groups showed very different anthropometric characteristics (Table 4.2.1): males were taller, heavier and leaner, which translates into greater MVs making their comparison unfair. However, when normalized to body size, these differences were not so evident. While hamstrings were still larger in males, quadriceps and adductors showed non-significant differences (Table 4.2.2 and Figure 4.2.2). To our knowledge, very little literature has focused on sex differences in sprinters MVs. Handsfield et al.[42] analyzed a group of male and female elite sprinters and found differences in absolute MVs. However, when MVs were normalized by height-mass, they found no differences in any lower-limb muscle, concluding that although females were shorter than their counterparts, MVs were proportional to body mass and height. Our results are in agreement with those of Handsfield and co-workers for quadriceps and adductors, but not for hamstrings. One possible reason for this discrepancy could be related to the performance level between groups. While Handsfield et al. did not report performance level, in our study, males presented higher performance levels than females (ES = 1.37, $P < 0.05$) (Table 4.2.1). This could be key in the case of hamstrings, due to the crucial role of this muscle group in sprinting.[70,75] In this regard, we found strong correlations with hamstrings MV and sprint performance (Figure 4.2.4).

As expected, males were faster than females, presenting extremely large differences, and they also exhibited greater SMPs with large to extremely large differences (Table 4.2.2 and Figure 4.2.3). In sprint events, the differences in performance between males and females are around 10%, when performance level is matched.[105] However, in our study, we found differences of 15%, probably due to the large differences in performance level (IAAF score) between sexes (Table 4.2.1). Aside from differences in performance that are intrinsic to gender, the males in this study belong to a superior sprint level. In addition, Slawinski et al.[1] compared the mechanical properties of women and men during 100 m finals of international events over the past 30 years, in order to understand the origins of differences in sprint performance. They found significantly higher F_0 (10.9%), V_0 (9.5%) and P_{max} (19%) in males, concluding that the differences in sprint performance between the sexes are due to a lower capability to produce force at high speeds in women, which in turn results in shorter acceleration phases, lower maximal speeds and longer deceleration phases.[1] As mentioned, differences in performance level between males and females may also partially explain the greater differences found in our study.

Several morphological characteristics, such as a taller frame, greater muscle mass, larger stride length and higher CM contribute to the male performance advantage in sprinting.[1,104] It has been suggested that faster top speeds are achieved with greater GRFs;[12,107] the larger absolute muscle mass that males possess represents an advantage when it comes to generating these forces.[12,104] Because sprint speed is also affected by step length and step frequency, the longer limbs and the increased muscularity of males contribute to a longer stride which also leads to a faster speed.[1,104] Additionally, marked structural differences in muscle and tendon stiffness have been reported,[1,96] being greater in males than in females. It is believed that lower-limb stiffness could influence sprint performance due to the major role played by stiffness in the stretch-shortening cycle.[1,15,107] In addition to the anthropometric and structural differences, studies of muscle characteristics have demonstrated that females have lower muscle glycolytic enzyme activities, as well as smaller cross-sectional type II fibres, than men; and this could also influence performance.[96,108]

Strong correlations were found between hamstrings MV, sprint performance and V_0 (Figure 4.2.4). Hamstrings have been reported to be key in producing propulsive forces in sprinting.[70,75] In recent literature it has been reported that hamstrings MV is a differential factor between sprinters and non-sprinters.[42,47] Moreover, our results add to previous literature correlating hamstrings MV with sprint performance,[46] which confirms the crucial role of this muscle group in sprinting. Adductors have also been reported to be important during sprinting.[48,49,70] Adductor magnus acts, in fact, as an important hip extensor, and the rest of adductors (pectineus, gracilis, adductor brevis and longus) as hip flexors.[70,81] In this regard we found moderate correlations with adductors MV and sprint performance and F_0 (Figure 4.2.4). Interestingly, adductors MV showed no correlation with V_0. From these results, two different assumptions can be made. First, hamstring muscularity might be more important than adductor muscularity in relation to sprint performance. As seen in Figure 4.2.4, hamstrings MV showed stronger associations with sprint performance. Second, adductors may play a more important role in the acceleration phase instead of maximum velocity phase, since F_0 represents the ability to produce horizontal force at very low velocities; in contrast, V_0 represents the ability to produce force at high velocities.[1,24] To this end, it seems that V_0, or a “velocity-oriented” profile is the main mechanical determinant of performance in sprinters.[1,11]

4.2.6 Conclusions

From the findings in this study it can be concluded that male sprinters had significantly larger hamstrings MV, while quadriceps and adductors showed no difference, compared with female sprinters. Males were extremely faster due to greater SMPs, especially maximal velocity. Moreover, strong correlations were found between hamstrings MV and sprint performance, supporting recent literature regarding the role of hamstrings muscularity in sprint performance. Finally, adductors MV showed moderate correlations with sprint performance, suggesting the importance of its muscularity in sprint performance, but to a lesser extent than hamstrings muscularity. This study provides valuable information to the field of research regarding sex differences in sprint performance.

4.3 Study III

Effects of sprint training.

4.3.1 Abstract

This study aimed to analyse changes in sprint performance, thigh MVs and SMPs in national-level sprinters performing a 5-month indoor sprint-based training macrocycle (SBTM). Twelve well-trained sprinters were tested on three different occasions throughout the SBTM. Testing procedures included: sprint performance over 10 m, 40 m, 80 m, 150 m, and 300 m; MRI of thighs, to compute MVs of quadriceps, hamstrings and adductors; and a 40 m sprint using a radar gun to assess SMPs such as F_0, V_0, P_{max} and D_{RF}. Improvements in sprint performance of between 4% and 7% (ES = 0.46-1.11, $P < 0.01$) were accompanied by increments in: quadriceps of 6% (ES = 0.41, $P < 0.01$), hamstrings of 10% (ES = 0.62, $P < 0.01$), adductors of 12% (ES = 0.87, $P < 0.01$), V_0 of 5% (ES = 0.40, $P < 0.01$) and D_{RF} of 7% (ES = 0.91, $P < 0.01$). In conclusion, during the SBTM after the off-season, moderate hypertrophic changes occur in sprinters. Moreover, the greater increase in hamstrings and adductors, compared with quadriceps, might be related to the prominent role of these muscle groups in sprinting. Furthermore, the SBTM was likely effective at developing sprint performance in sprinters, thereby endorsing the idea that sprint-specific training is crucial for highly trained individuals. Finally, our results support the notion that V_0 or the "velocity-oriented" F-V profile is determinant of performance in sprinters.

Keywords: *Sprint performance, Muscle volume, Sprint mechanical properties, Magnetic resonance imaging, Sprinter training.*

4.3.2 Introduction

Sprint ability is a key factor in many sports and hence the focus of many training programmes. Although many factors influence sprint performance, it has recently been shown that the propulsive forces produced during sprinting are the strongest predictor of acceleration and sprint performance.[8,10,18] Moreover, the ability to orientate the GRF vector forward is also the differential factor between recreational and top-level sprinters.[8] The overall mechanical capability to produce horizontal forces is estimated by the inverse linear F-V and P-V relationships. These relationships characterise the mechanical limits of the entire neuromuscular system and are well explained by the F_0, the theoretical maximal velocity the system can develop when force is equal to zero (V_0), together with the associated P_{max}.[24]

Force production seems to be largely determined by muscle mass.[38] When comparing sprinters with an average population, the differences in muscularity are evident.[42,43] However, it is known that changes in muscle shape induced by training are not uniform along the muscle.[62] This fact evidences the limitations of a single CSA measurement, which might not be sufficient to gauge hypertrophic changes. In addition, joint torque and power generation capabilities are largely determined by MV rather than CSA.[37,39] Hence, it seems logical to believe that MV could play an important role in sprint performance. Some authors have worked on this hypothesis, finding strong relationships between different leg MVs and both maximal running speed and acceleration capacity.[49,101] In this regard, Perez-Gomez et al.[96] analysed the role of the lean lower body mass in sprint performance and found that the total muscle mass of the legs is strongly correlated with sprint performance. In a recent study comparing two elite groups of sprinters and endurance athletes, Bex et al.[43] found differences in MVs, especially in the thighs, suggesting the relevance of upper leg muscle groups in sprint performance.

In a recent paper, Bezodis et al.[14] analysed how training periodisation influences sprint performance in a group of elite sprinters, finding that the improvements in sprinting speed are, mainly, due to increases in step frequency. In contrast, findings from Nagahara et al.[15] revealed that improvements in maximal velocity over a full winter season were due to increments in step length and vertical stiffness. However, the few literature studying the effects of periodised training seems focused on spatiotemporal variables. The studies analysing muscularity and sprint performance are cross-sectional, thus, it seems there is a lack of long-term investigation about hypertrophic and sprint performance changes in sprinters. Therefore, in this study, we analysed the effect of a 5-month SBTM on sprint performance. Moreover, aside from the assessment of fitness in sprinters, a better understanding of which muscular and mechanical changes accompany potential sprint performance enhancements might be highly beneficial for the development and control of training plans. Therefore, the aim of the present study was to analyse changes in sprint performance, as well as in thigh MVs and SMPs, in national-level sprinters during an SBTM.

4.3.3 Methods

Participants

Twelve well-trained adult sprinters (men=6; women=6) (age: 23.5 ± 4.1 years; body mass: 65.0 ± 12.3 kg; height: 172.1 ± 11.8 cm) volunteered to participate in the study. The gender, athletic event speciality and personal best times of the athletes are provided in Table 4.3.1. The inclusion criteria were: (1) sprinters who compete in races over 100 m to 400 m at a national level; (2) preparing for the 2017 indoor season; and (3) free from lower limb soft tissue injuries for the previous 4 months. The exclusion criteria were: (1) medical problems contraindicated for experimental testing; and (2) not having completed at least 80% of the training sessions at the end of the study. Initially, fifteen athletes were recruited, although three of them were forced to withdraw from the study, due to injuries during the SBTM. All the participants gave written informed consent to participate in this study, which was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of the Catalan Sports Council (Generalitat of Catalonia) (0099S/690/2013).

Participant	**Sex**	**Event**	**Event PB** (s)
01	Female	400 m	58.39
02	Female	400 m	58.97
03	Male	100 m	11.21
04	Female	200 m	24.98
05	Female	200 m	25.32
06	Female	200 m	26.87
07	Male	100 m	10.95
08	Female	400 m	59.19
09	Male	200 m	21.13
10	Male	400 m	48.14
11	Male	100 m	11.06
12	Male	100 m	10.71

Table 4.3.1 Sprinter's individual sex and event characteristics from study III.

Design

The study was designed as an ecological (no interference with athlete training schedules) follow-up of an indoor SBTM (from September to February). During the training period, the athletes were tested on three different occasions: the week before starting the SBTM (PRE); exactly in the middle of the SBTM (IN); and at the end of the SBTM, two weeks before the Spanish National Indoor Championship, (POST). Therefore, two different periods of training with the same duration were differentially assessed by the tests: period 1, from PRE to IN (P_1);

and period 2, from IN to POST (P_2). The 10 m and 40 m sprint tests, and the SMPs test were recorded during the same sprint. In all the sprint tests, the athletes adopted the three-point start position, using their usual competitive spikes. All the tests were performed in the same order, at the same time and under the same conditions during PRE, IN and POST (Figure 4.3.1).

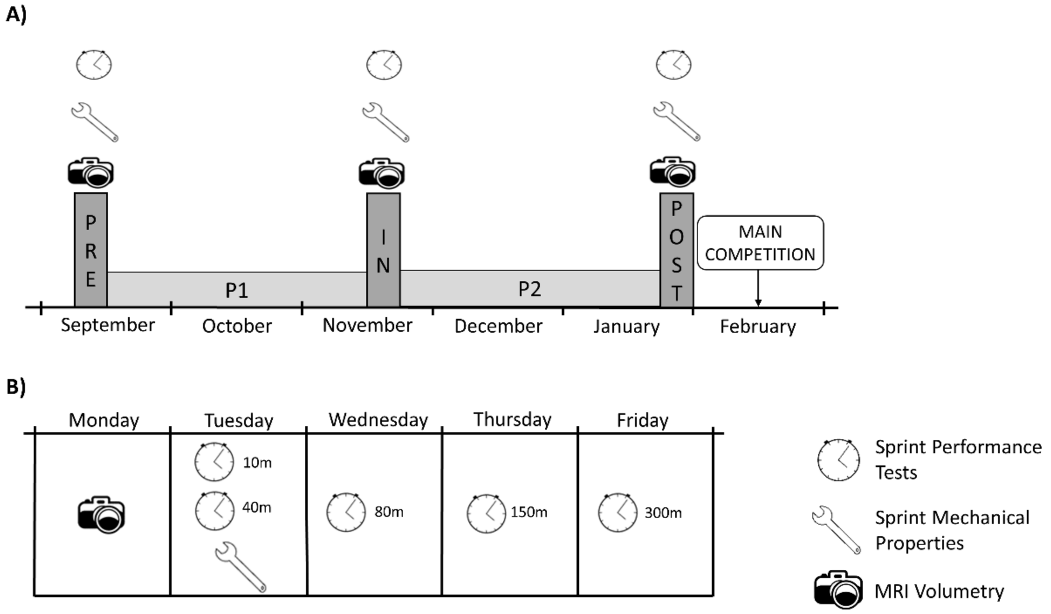

Figure 4.3.1 Schematic overview of design and procedures of study III.

A) Schematic overview of the experimental design. A total of three testing periods were spread over the indoor athletics season. All the tests were repeated in the same order and under the same conditions.
B) Schematic overview of the testing procedures throughout the testing week.
PRE, Pre-training test. IN, In-training test. POST, Post-training test. P_1, period of training between PRE and IN. P_2, period of training between IN and POST.

Sprint performance

To assess the whole spectrum of maximal anaerobic power distances for the sprinter, we included: 10 m, 40 m, 80 m, 150 m and 300 m tests. In fact, the training of all sprinters is composed of different sprint distances, in order to train the different phases of the sprint (i.e., acceleration, maximum speed and speed-endurance); thus, the distances included in this study may help to elucidate specific improvements. In order to avoid interference with the athletes' training schedules, the sprint tests were carried out as follows: Tuesday 10 and 40 m, Wednesday 80 m, Thursday 150 m and Friday 300 m (Figure 4.3.1). After 40 min of standard warm-up led out by their coach, the athletes started the tests. Microgate Witty photocells (Microgate, Italy) were used to measure the times, and were activated when crossed. The athletes started their attempts just before the first photocell, and the timer started at their very first movement. In order to have a faster and more reliable start, the participants were told to start at will: when they wanted.

As stated before, the 10 m and 40 m sprint tests were conducted over the same sprint, during which the SMPs were also recorded. Three pairs of photocells were positioned at distances of 0, 10 and 40 m. The athletes performed two trials with 6 min rest in between. For the 80 m sprint test, two pairs of photocells were placed at distances of 0 and 80 m. The athletes again performed two attempts with 15 min rest in between. For the 150 m and 300 m tests, only one attempt was performed, and two pairs of photocells were placed at distances of 0 and 150 m, and 0 and 300 m, respectively. The best time over each sprint distance was used for further analysis.

Muscle volumes

For MV assessment, series of cross-sectional images of each subject's thighs were obtained by MRI with an Avanto 1.5T (Magnetom Avanto, Siemens Healthineers, Germany). Transaxial images (slice thickness, 2mm; increment, 2mm) were acquired in a 320x320 matrix, 40x40 field of view in 20-second blocks. The volunteers were placed supine inside the scan with their heads outside the MR bore, thighs covered with a leg coil and limb position was fixed with a custom-made foot restraint. Between 280 and 320 (depending on each subject's thigh length) images of both legs were obtained from the iliac spine to the patella. All scans were performed on Monday, after at least 48 h of recovery after the previous training session, to account for hypertrophic changes and avoid any influence of acute muscle swelling.[92]

VL, VI, VM and RF were outlined together and identified as quadriceps. BFlh, BFsh, ST and SM were outlined together and identified as hamstrings. The same approach was adopted for the assessment of adductors MV, which included adductor magnus, adductor longus, adductor brevis, adductor minimus, pectineus and gracilis. The edges of the quadriceps, hamstrings and adductors were manually outlined image by image, by the same researcher, following the reference method proposed by Nordez et al.,[53] using Osirix 8.5.2 (Pixmeo, Geneva, Switzerland). The total volume of each muscle was calculated from the range between the last image in which the ischial tuberosity was visible and the last image where the muscle was visible (Figure 4.3.2). MV results are shown as the average of right and left thighs. The intra-investigator coefficient of variation for muscle segmentation was 1.1% ± 0.4% for the muscles assessed; similar to previous estimations of error using this method.[53,93]

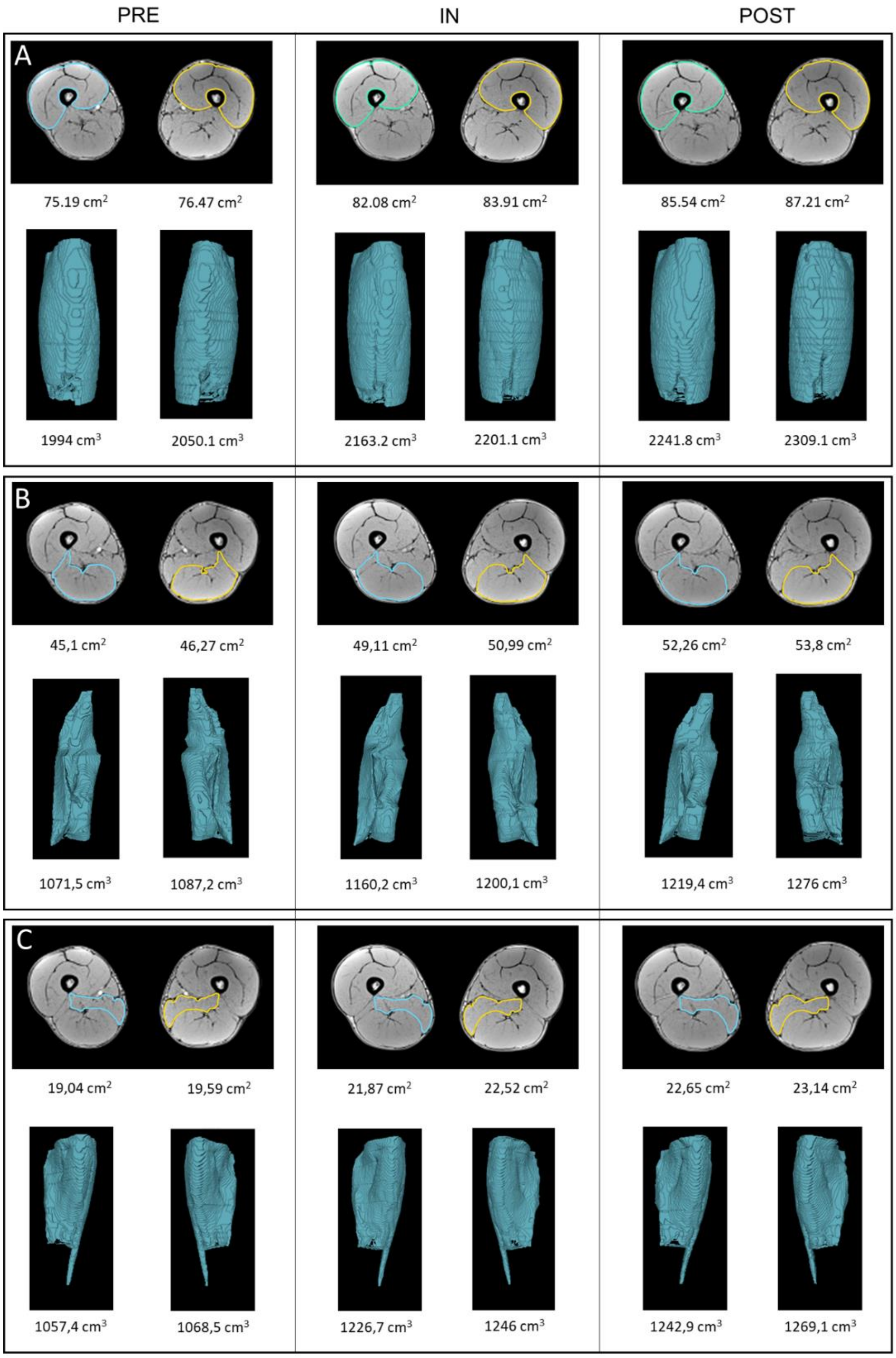

Figure 4.3.2 Muscle volumes reconstruction from study III.

Representative example of changes in cross-sectional area (≈ 50% length of the thigh) and muscle volumes of right and left thighs during the period (subject no. 7). Representative images of the (A) quadriceps, (B) hamstrings and (C) adductors muscle groups.
PRE, Pre-training test. IN, In-training test. POST, Post-training test.

Sprint mechanical properties

Instantaneous velocity over a 40 m sprint was measured by radar (Stalker ATSII, Plano, Texas, USA) with a sampling rate of 48 Hz, as previously validated in human sprint experiments.[18,24] The device was placed on a tripod 2 m behind the subject at a height of 1 m: approximately the average subject's CM. Subjects were instructed to keep static the starting position for about one second, in order to record a "0 velocity" signal, and then to start running forward without any countermovement. The fastest trial, based on photocell times, was selected for further analysis. The resultant data were subsequently analysed using the simple field method validated by Samozino et al.[24] Briefly, this computation method is based on macroscopic inverse dynamics analysis of the CM motion. Velocity-time data are fitted to an exponential function, after which instantaneous velocity is derived to compute the net anteroposterior GRF and power. Individual F-V relationships are then extrapolated to calculate F_0 and V_0 capabilities, and the underlying P_{max}, as described elsewhere.[8,18,24] The D_{RF} was also calculated from the linear F-V relationship, which represents the ability to apply horizontal force as running speed increases.[8,24]

Sprint-based training macrocycle

For the study to be ecological, we did not interfere in the athletes' training processes; we did, however, exhaustively record the daily training regime of each athlete. A training diary was used to quantify the real, not the planned, external training load. Similar weekly organization was followed during the SBTM, with training taking place of five days out of seven, as follows. Mondays: sprint-technique drills, plyometrics and short-distance sprints from 10 to 80 m; Tuesdays: resistance-training, plyometrics and sled-resisted sprint; Wednesdays: sprint-technique drills and long-distance sprints from 150 to 400 m; Thursdays: rest day; Fridays: resistance-training, plyometrics and sled-resisted sprint; Saturdays: sprint-technique drills and short- to middle-distance sprints from 60 to 150 m. It must be noted that the long-distance sprints included in

Wednesday training differed between “short-distance sprinters” and “long-distance sprinters”, with slightly shorter distances for the firsts (i.e., 300 m vs. 500 m). The SBTM was mostly composed of sprint-specific training, and linear periodization was used to improve performance, starting with relatively large volumes and low intensities, and progressively reducing the former and increasing the latter.

For the sprinting, the time and distance of each run were recorded. For sled-resisted sprint, the number of sprint bouts and the load relative to bodyweight were registered (the distance was 20 m). For sprint-technique drills, the number of runs and the different types of drills were recorded (the distance was 30 m). For resistance-training, the number of sets, repetitions and weight (relative to repetition maximum or body weight) were recorded. For plyometrics, the total numbers of horizontal and vertical jumps were also registered (Figure 4.3.3).

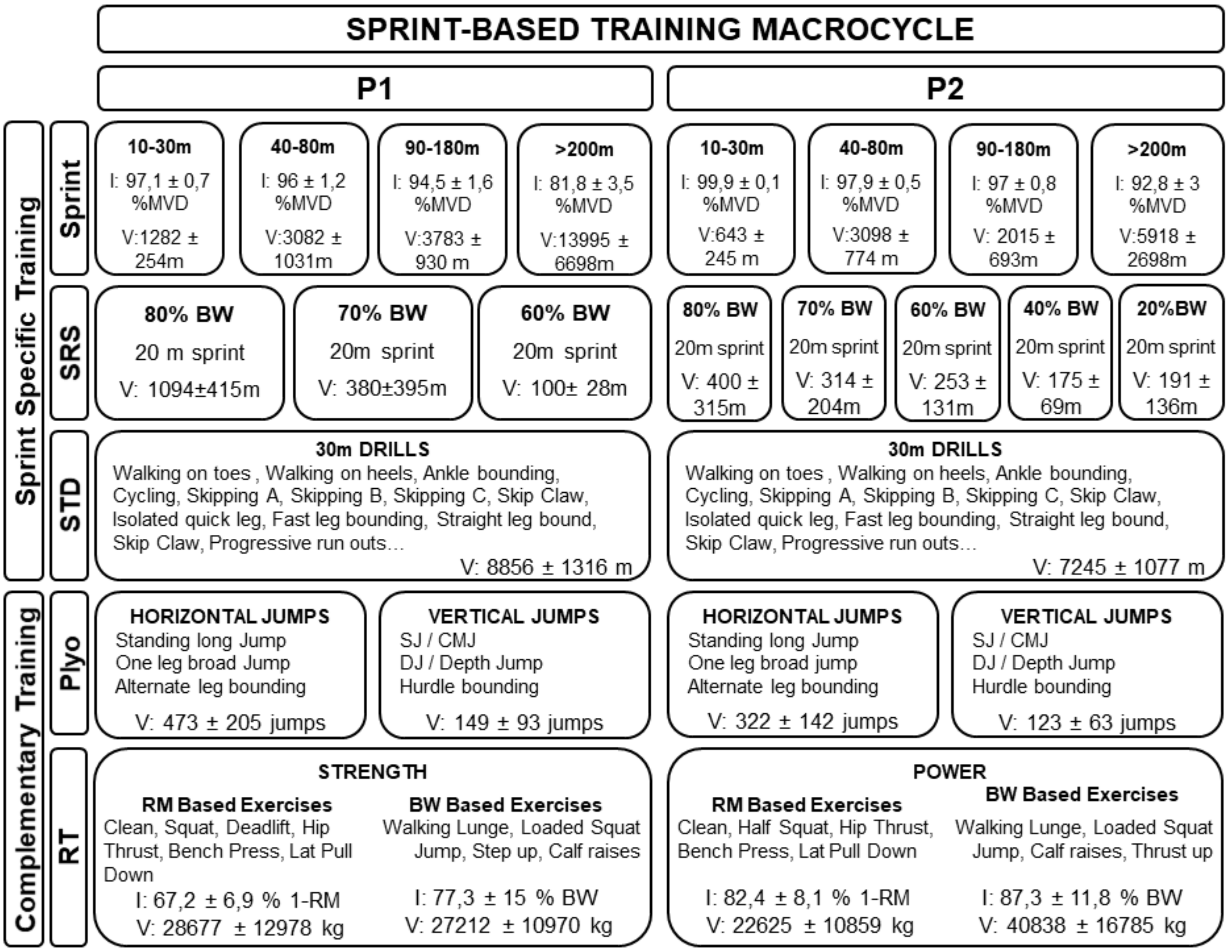

Figure 4.3.3 Schematic overview of the sprint-based training macrocycle from Study III.

P_1, First training period (from Pre-training tests to In-training tests). P_2, Second training period (from In-training tests to Post-training tests). Sprint, Sprint training. I, Intensity. MVD, Maximal velocity over the distance. V, Volume. SRS, Sled-resisted sprinting. BW, Body weight. STD, Sprint technique drills. Plyo, Plyometric training. SJ, Squat jump. CMJ, Counter movement jump. DJ, Drop jump. RT, Resistance training. RM, Repetition maximum. Data is presented as mean ± standard deviation.

Statistical analysis

All data are presented as mean ± SD. Statistical analysis was performed using SPSS v.23.0.0.0 (IBM, Armonk, New York). The normal distribution of the data was checked using the Shapiro-Wilk test. One-way repeated-measures ANOVA was used to identify the effect of time on the different variables analysed. If significant effects were found, a *post-hoc* Bonferroni corrected paired *t*-test was applied to identify significant differences between PRE, IN and POST values. Statistical significance was set at $P < 0.05$. ESs (Cohen's d) were calculated to compare the magnitude of the differences between PRE, IN and POST.[94] Due to the great anthropometric variability between subjects (i.e.: 88 kg heaviest male vs. 52 kg lightest female) that affects the SD of averaged MVs, these values were normalised by height-mass in order to have a more accurate ESs, which depends on the magnitude of the SD.[42] Pearson's correlation coefficient was employed to evaluate the association between the normalised MVs and sprint performance at POST, with thresholds being 0.40-0.59, moderate; 0.60-0.79, strong; 0.80-1, very strong.

4.3.4 Results

Data for the different variables (sprint performance, normalised MVs and SMPs) measured at PRE, IN and POST, are presented in Table 4.3.2.

Variable measured	**PRE**	**IN**	**POST**	**ES** (Pre vs. In)	**ES** (In vs. Post)	**ES** (Pre vs. Post)
Sprint performance						
10 m (s)	2.00 ± 0.14	1.98 ± 0.13	1.86 ± 0.11$^{**\#\#}$	-0.15	-1.00	-1.11
40 m (s)	5.70 ± 0.49	5.65 ± 0.44	5.42 ± 0.42$^{**\#}$	-0.11	-0.54	-0.61
80 m (s)	10.30 ± 0.95	10.02 ± 0.86**	9.84 ± 0.86**	-0.31	-0.21	-0.51
150 m (s)	19.34 ± 1.86	18.76 ± 1.80**	18.47 ± 1.94**	-0.32	-0.16	-0.46
300 m (s)	42.78 ± 4.64	41.45 ± 4.41**	40.59 ± 4.20$^{**\#\#}$	-0.29	-0.20	-0.50
Muscle volumes						
Quadriceps (cm^3·kg^{-1}·m^{-1})	16.17 ± 2.53	17.03 ± 2.39**	17.20 ± 2.47**	0.35	0.07	0.41
Hamstrings (cm^3·kg^{-1}·m^{-1})	7.75 ± 1.16	8.45 ± 1.24**	8.53 ± 1.35**	0.58	0.06	0.62
Adductors (cm^3·kg^{-1}·m^{-1})	8.69 ± 1.15	9.70 ± 1.27**	9.74 ± 1.27**	0.83	0.03	0.87
Sprint mechanical properties						
F_0 (N/kg)	8.0 ± 0.9	7.5 ± 0.9	7.7 ± 1.1	0.56	0.20	0.30
V_0 (m/s)	8.8 ± 1.0	9.0 ± 0.9**	9.2 ± 1.0**	0.21	0.21	0.40
P_{max} (W/kg)	17.7 ± 4.0	16.9 ± 3.4	17.9 ± 3.9	-0.22	0.27	0.05
D_{RF}	-0.072 ± 0.005	-0.068 ± 0.005*	-0.067 ± 0.006**	0.80	0.18	0.91

Table 4.3.2 Variables measured from study III.

*PRE, Pre-training test. IN, in-training test. POST, Post-training test. ES, Effect Size. 10 m, time achieved over 10 m sprint. 40 m, time achieved over 40 m sprint. 80 m, time achieved over 80 metre sprint. 150 m, time achieved over 150 m sprint. 300 m, time achieved over 300 metre sprint. F_0, theoretical maximal horizontal force. V_0, theoretical maximal horizontal velocity. P_{max}, theoretical maximal horizontal power. DRF, rate of decrease of ratio of force with increasing speed, during sprint acceleration. Values are mean ± SD of the group of athletes. * Indicates significant difference from PRE value, at $P < 0.05$. ** Indicates significant difference from PRE value, at $P < 0.01$. $^{\#}$ Indicates significant difference from IN value, at $P < 0.05$. $^{\#\#}$ Significantly different from IN value, at $P < 0.01$.*

Sprint performance

Sprint performance improved throughout the SBTM. The 10 m and 40 m times were reduced significantly from PRE to POST: by 7.0% and 4.9% (ES = -1.11 and -0.61, $P < 0.01$) respectively; and from IN to POST: 5.6% and 3.3% (ES = -1.00 and -0.54, $P < 0.05$) respectively, although no significant changes were seen from PRE to IN. The 80 m and 150 m times were significantly reduced from PRE to IN: 3.2% and 3.4% (ES = -0.31 and -0.32, $P < 0.01$) respectively; and from PRE to POST: 4.4% and 4.5% (ES = -0.51 and -0.46, $P < 0.01$) respectively, but here there were no significant changes from IN to POST. Significant time reductions were seen at all points in the 300 m sprint test; with 3.6% (ES = -0.29, $P < 0.01$) from PRE to IN, 1.8% (ES = -0.20, $P < 0.01$) from IN to POST and 5.1% (ES = -0.50, $P < 0.01$) from PRE to POST. Absolute values of sprint performance are shown in Table 4.3.2.

Muscle volumes

The MVs of the three muscle groups analysed increased throughout the SBTM. Quadriceps increased 5.6% (ES = 0.35, $P < 0.01$) from PRE to IN and 6.7% (ES = 0.41, $P < 0.01$) from PRE to POST. Hamstrings increased 9.2% (ES = 0.58, $P < 0.01$) from PRE to IN and 10.1% (ES = 0.62, $P < 0.01$) from PRE to POST. Adductors increased 11.7% (ES = 0.83, $P < 0.01$) from PRE to IN and 12.1% (ES = 0.87, $P < 0.01$) from PRE to POST. Normalised values of MVs are presented in Table 4.3.2, whereas absolute values are displayed in Figure 4.3.4.

Normalised hamstrings MV was strongly correlated with all sprint distance times (range: r = -0.727 to -0.796, $P < 0.01$). Normalised adductors MV was strongly associated with 40 m, 80 m and 150 m sprint times (r = -0.689; -0.688; -0.680, $P < 0.05$, respectively). Normalised quadriceps MV was only associated with 40 m sprint time (r = -0.644, $P < 0.05$).

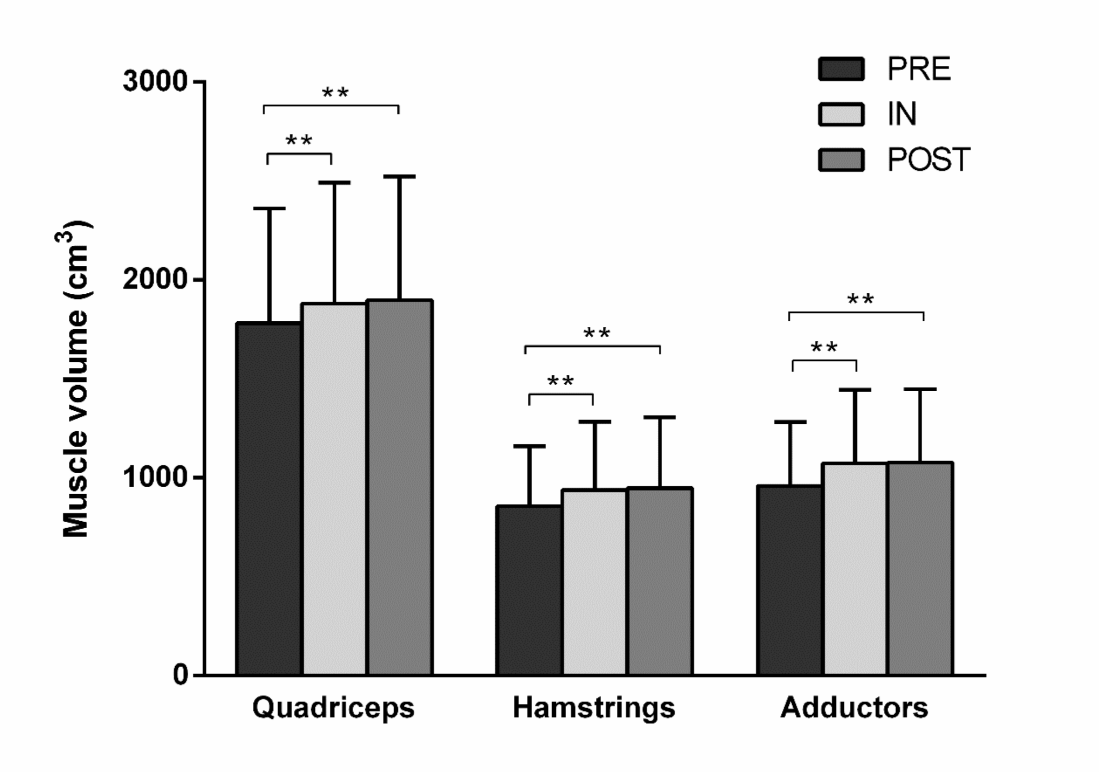

Figure 4.3.4 Absolute changes in muscle volumes through the training period from Study III.

*PRE, Pre-training test. IN, In-training test. POST, Post-training test. ** Indicates significant differences from PRE value, at* $P < 0.01$.

Sprint mechanical properties

A significant increase in V_0 of 3.7% (ES = 0.21, $P < 0.01$) was seen from PRE to IN; and 5.3% (ES = 0.40, $P < 0.01$) from PRE to POST. Similarly, D_{RF} improved by 6.2% (ES = 0.80, $P < 0.05$) from PRE to IN; and by 7.2% (ES = 0.91, $P < 0.01$) from PRE to POST. No significant changes were seen in either V_0 or D_{RF} from IN to POST. No significant changes were seen in either F_0 or P_{max}. Absolute values of SMPs are shown in Table 4.3.2.

4.3.5 Discussion

The aim of this study was to analyse changes in sprint performance, MVs and SMPs in national-level sprinters during an indoor SBTM. We found that the SBTM was likely effective in developing sprint performance and the improvements were accompanied by a significant increment of the thigh muscle groups measured (quadriceps, hamstrings and adductors). Interestingly, the relative increase in hamstrings and adductors MVs was almost the same, and doubled the relative increase in quadriceps. Finally, performance enhancement was accompanied by significant increases in V_0 and D_{RF}, confirming that these parameters seem to be the most determinant of performance in sprinters.

Small to moderate improvements in sprint performance occurred throughout the SBTM. Interestingly, greater improvements over short distances (i.e. 10 m and 40 m) took place during P_2; while slightly greater improvements over longer distances (i.e. 80 m to 300 m) took place during P_1 (Table 4.3.2). Lower volumes and higher intensities are expected to improve sprinting speed. In fact, in a recent study analysing the effects of an extended training period on sprinters, Bezodis et al.[14] found that improvements in sprint performance occurred during training phases of low-volume lifting and high-intensity sprint work. However, in our work, P_1 involved higher volumes and lower intensities than P_2 (Figure 4.3.3); thus, our results are partially in accordance with those of Bezodis et al.[14] We should also mention that in our study the athletes started in a highly detrained status, after 6 weeks of rest, thus the margin for improvement that they had in P_1 was much greater than that in P_2.

Our results are also in agreement with Rumpf et al.[109] who found that while complementary training modalities, such as resistance-training (strength and power) and plyometric training, influence sprinting speed to some extent, sprint-specific training (sprinting, sled-resisted sprint and sprint-technique drills) was crucial to ensure performance improvements over different distances (ranging from 10 to > 30m) in athletes from different sports disciplines.

Sprint performance enhancements were accompanied by significant MV increases in all three muscle groups analysed. Moderate increases were found in hamstrings and adductors, whereas small increases were found in quadriceps. Moreover, we observed a highly consistent pattern of change in all three muscle groups analysed, with increases in P_1 (from PRE to IN) and maintenance during P_2 (from IN to POST) (Figure 4.3.4).

Since the sprinters were enrolled on an SBTM which was mainly composed of sprint-specific training, the moderate increase in hamstrings MV might be linked with the crucial role of this muscle group in sprinting. In this regard, hamstrings MV showed strong correlations with all sprint distance times analysed. Previous studies have found a peak in hamstring activity from mid swing until terminal stance.[72,75] In the mid and late swing, the hamstrings work eccentrically to decelerate the knee extension; and then during the whole stance phase, they work concentrically, as hip extensors, to produce forward movement.[70,77] The amount of horizontal GRFs produced during sprinting acceleration is related to hamstring activation just before ground contact and eccentric knee flexor peak torque.[72,75] Moreover, hamstrings are key hip extensor muscles, showing a large and stable moment arm in the whole sagittal hip range of motion [80].

It is well documented that adductor magnus is a powerful hip extensor when the hip is flexed [79–81]. In contrast, the other adductors (pectineus, adductor longus, adductor minimus, adductor brevis and gracilis) are in fact hip flexors, especially when the hip is extended [79–81]. In the early swing, when hip flexors are stretched, adductors play an important role in assisting hip flexion, and in neutralising the abduction and external rotation caused by tensor fascia latae and sartorius [70]. Meanwhile, during the mid to late swing, when the hip is flexed, adductors work as a synergist of gluteus maximus, helping with hip extension and counterbalancing its external rotation. In this sense, we found strong associations between adductors MV and 40 m, 80 m and 150 m sprint times. Furthermore, Tottori et al.[49] studied the relation between adductors and sprint performance in preadolescent sprinters, and showed that larger adductors are related with better sprint performance. Even though these results cannot be directly compared with ours, there might be some similarities. Taking into account the importance of adductors in sprint-specific training and in complementary training, the moderate adductors MV increment observed in our work could reasonably be expected.

Despite the importance of knee extensors in sprinting and their contribution to generating vertical GRFs,[49,69,70] it seems that quadriceps only contribute in the forward acceleration during the first steps, when the body leans forward due to the projection of the CM, ahead of the support base [70,77]. When sprinting, knee extensor activation is required during the stance, first to decelerate the vertical displacement of the CM and to stabilise the knee joint, and then to accelerate the CM vertically.[70] Recent literature supports the idea that the muscularity of the quadriceps is not related with sprint performance;[46,50] however, this is still a matter of debate. In the present study, quadriceps MV was only correlated with 40 m and to a lesser degree than for hamstrings and adductors. It seems that enlargement of these muscles would increase the lower limb moment of inertia and hence reduce the limb angular acceleration.[46] The lesser contribution of quadriceps during sprinting compared to hamstrings and adductors, might explain the smaller increase found in them.

Another finding of this study is the time course of the hypertrophic process, with moderate increases in MVs during P_1 and maintenance in P_2 (Table 4.3.2 and Figure 4.3.4). We therefore worked with two different hypotheses concerning the cause of this: 1) the prior detraining process, since athletes started the SBTM after 6 weeks of rest; and 2) the relatively large training volumes achieved in P_1 in comparison with P_2 (Figure 4.3.3) throughout the SBTM. During the detraining period, the fastest rate of muscle atrophy, especially the degradation of contractile protein, takes place in the first two weeks.[28] These changes result from lower glycogen content in the muscle, and especially from protein breakdown, as a result of inhibition of anabolic cellular pathways.[110] Moreover, it has been reported that after sprint training, there is a loss of muscle fibre CSA of 5% to 13% over a period of two to seven weeks after the cessation of training.[28] However, Bruusgaard et al.[111] showed that muscle acquires newly formed myonuclei after a training process, which are not lost during detraining and the subsequent atrophy; this thereby accelerates the incoming hypertrophic process and explains why previously trained individuals are more easily retrained. In addition, Seaborne et al.[112] identified some epigenetically sensitive genes with enhanced expression after the detraining process, which result in almost twice the hypertrophic changes after retraining. Furthermore, it is assumed that training volume is a crucial factor for hypertrophy;[113] here, higher training volumes are observed in P_1 than in P_2 (Figure 4.3.3). Therefore, loss of MV during detraining and newly formed myonuclei, together with higher training volumes, could explain the larger increases in MVs following P_1 compared to P_2.

Enhanced sprint performance was also accompanied by significant changes in SMPs. V_0 and D_{RF} were significantly improved from PRE to IN and from PRE to POST (Table 4.3.2). These improvements mean that after the SBTM, the athletes were able to achieve higher maximum speeds and to apply force onto the ground more effectively over the entire acceleration.[8] In other words, following the SBTM, athletes shifted their individual F-V profile towards “velocity-oriented”. Along similar lines, Morin et al.[11] found that V_0 and D_{RF} are the most determinant variables predicting sprint performance, as well as the variables that differ the most when comparing elite with average sprinters (they found no differences in F_0). Thus, when we analysed 40 m, 80 m and 150 m performance, which presumably are more closely determined by V_0, we found an expected improvement; this is also in accordance with the conclusions of Morin et al.[8,11] and Rabita et al.[18]

F_0 is related to very initial acceleration capabilities, since it is the theoretical maximal horizontal force a subject can apply onto the floor.[8,24] Despite part of the training being oriented to improving acceleration, F_0 did not change during the SBTM. One reason that might explain this is that F_0 is the theoretical maximal horizontal force at zero velocity, which is not the actual case during acceleration, where the velocity is increasing right from the first moment. In contrast, D_{RF}, or the ability to apply horizontal force during the acceleration phase, showed a significant increase. Nevertheless, the improvement in 10 m sprint performance without any change in F_0 is remarkable. Finally, since power output is the product of force and velocity, the maintenance of P_{max} seems reasonable, because of the absence of changes in force capabilities.

4.3.6 Conclusions

The SBTM was likely effective in developing sprint performance over all the distances assessed in national-level athletes. Sprint performance enhancements were accompanied by significant increases of quadriceps, hamstrings and adductors MVs, especially during P_1, when higher training volumes were achieved. This supports the notion that training volumes have a crucial impact on hypertrophy. Moreover, the relatively higher hypertrophic changes of hamstrings and adductors, compared to quadriceps, might be related to the prominent role of the former muscle groups in sprinting. Finally, sprint performance increases were also accompanied by an enhancement of SMPs, supporting the notion that V_0 or the “velocity-oriented” F-V profile is determinant of performance in sprinters.

5 DISCUSSIÓ

L'objectiu de la present tesi doctoral va ser analitzar la influència que tenen els MVs dels diferents grups de la cuixa sobre el rendiment en esprint en diferents poblacions. A més també es va estudiar l'adaptació d'aquests grups musculars a un període d'entrenament específic d'esprint amb un grup de velocistes de nivell nacional.

Per tal d'entendre la influència del desenvolupament muscular i les SMPs en el rendiment en l'esprint, i les adaptacions musculars que l'entrenament d'esprint comporta es discutiran de manera global els resultats dels tres estudis que conformen la present tesi. Primer s'analitzaran les diferències entre població velocista i no velocista, després les diferències entre sexes de velocistes i finalment les adaptacions musculars que tenen lloc després d'un període de 5 mesos d'entrenament d'esprint en velocistes de nivell nacional.

5.1 Rendiment en l'esprint

5.1.1 Velocistes vs. no velocistes

Com era d'esperar, els velocistes van ser molt més ràpids i van presentar unes SMPs molt superiors a les de la població activa (Taula 4.1.2, pàg. 83) (Estudi I). Els temps per cobrir 10 m i 40 m van ser un 7 % (ES = 2,12; $P < 0,001$) i un 11 % (ES = 3,68; $P < 0,001$), respectivament, més baixos per als velocistes. A més la V_0 i la P_{max} van ser un 20 % (ES = 4,53; $P < 0,001$) i un 28 % (ES = 3,04; $P < 0,001$) més altes en el grup de velocistes. Curiosament la F_0 no va presentar diferències significatives entre grups, encara que moderadament més alta per als velocistes (ES = 0,80). Els nostres resultats coincideixen amb els exposats per Morin et al.,[8,11] els quals, comparant velocistes d'alt nivell amb població activa, reportaren grans diferències en V_0 i en P_{max}, mentre que la F_0 no va mostrar diferències significatives. D'aquests resultats se'n poden extreure diferents conclusions. La magnitud de les diferències en el rendiment en esprint augmentava concomitantment amb la distància recorreguda (10 m vs. 40 m), a més, es pot especular que a més distància aquestes diferències haurien augmentat més degut a les enormes diferències en V_0 (ES = 4,53) (Taula 4.1.2, pàg. 83). La V_0 és la velocitat màxima teòrica i representa l'habilitat de l'atleta de produir forces anteroposteriors a alta velocitat.[18,24] A banda d'això, la V_0 ha mostrat correlacions molt altes amb el rendiment en 100 m[1,8,11] i semblaria que pot estar més lligada amb el rendiment en distàncies més grans que 10 m i 40 m.[1] Sí que és cert que als 40 m, els participants ja havien aconseguit la velocitat màxima o hi estaven molt a prop, però durant la major part de l'esprint de 40 m els atletes estan accelerant, per tant la velocitat mitjana en aquesta distància poc té a veure amb la V_0. Per contra, en un esprint de 80 m, la velocitat mitjana és més alta que en un de 40 m, per tant, el temps en què es corre a velocitat màxima, o propera a la màxima, és més elevat, això explica que la V_0 estigui més relacionada amb distàncies més grans que 10 m i 40 m. Dit això, veiem que els velocistes acceleraven molt més ràpid que el grup d'actius, però, sobretot, van ser extremadament més ràpids a velocitats màximes. Aquests resultats semblen raonables, ja que els velocistes analitzats aquí eren especialistes en 100 m llisos, i els actius estaven acostumats a accelerar sobre distàncies relativament curtes (10-30 m) degut als seus antecedents de participació en esports col·lectius.

Atès que no es van trobar diferències significatives entre grups en la F_0, les diferències en rendiment entre velocistes i població activa sembla que estan relacionades amb les enormes diferències trobades en P_{max} i V_0. Aquest perfil de P-F-V característic dels velocistes s'explica per la capacitat d'aplicar majors GRFs anteroposteriors a velocitats altes, i pot estar relacionat tant amb propietats neuromusculars (fibres ràpides, impulsos nerviosos més potents i elevada *stiffness* musculotendinosa entre d'altres), com amb l'habilitat tècnica d'orientar endavant les GRFs durant l'esprint.[8,18,24]

5.1.2 Homes vs. dones velocistes

Una vegada analitzades les diferències en rendiment i SMPs entre velocistes i població jove i activa volíem veure com es diferenciaven els velocistes de diferent sexe. Després d'analitzar un grup d'homes i dones velocistes de nivell nacional

(Estudi II), vam veure que els homes eren molt més ràpids i mostraren unes SMPs molt superiors a les dones (Taula 4.2.2, pàg. 100, i Figura 4.2.3, pàg. 102). Ja que en aquest cas tota la mostra estava especialitzada en proves atlètiques de velocitat, vam optar per analitzar distàncies més llargues (40 m i 80 m) i més representatives del rendiment per a un velocista. Els homes van ser un 14 % (ES = 6,68; $P < 0{,}001$) i un 15 % (ES = 5,01; $P < 0{,}001$) més ràpids en 40 m i en 80 m, respectivament. Pel que fa a les SMPs, els homes mostraren major F_0 (19 %; ES = 1,98; $P < 0{,}01$), P_{max} (46 %; ES = 3,76; $P < 0{,}001$) i V_0 (23 %; ES = 6,97; $P < 0{,}001$). En definitiva, i com era d'esperar, els homes mostraren un rendiment molt superior a les dones. En proves de velocitat (100 m a 400 m) i comparant homes i dones del mateix nivell, les diferències en el rendiment són de l'ordre del 10 %,[104,105,114] malgrat això, en el nostre treball les diferències van ser del 15 %. Val a dir que en el nostre estudi, el grup d'homes analitzats eren superiors a les dones segons la classificació que fa la IAAF (Taula 4.2.1, pàg. 99) basada en la seva millor marca personal. La IAAF proposa unes taules, basades en els rècords mundials, per poder comparar el rendiment en diferents proves i entre sexes. Aquestes diferències en rendiment (classificació de la IAAF) podrien explicar aquest 5 % de superioritat, respecte al 10 % exposat per altres autors,[104,105] que mostren els homes en el nostre treball.

Amb l'objectiu de trobar on residien les diferències en rendiment entre homes i dones, Slawinski et al.[1] van analitzar finals de 100 m de nivell internacional dels últims 30 anys. Aquests investigadors van trobar que els homes posseïen la F_0 (11 %; $P < 0{,}01$), la V_0 (10 %; $P < 0{,}01$) i la P_{max} (19 %; $P < 0{,}01$) més altes que les dones, així mateix explicaren que les diferències en rendiment eren degudes a la major capacitat que tenen els homes de produir GRFs anteroposteriors a altes velocitats. Com s'ha explicat abans, aquest fet està estretament lligat al fet de tenir una V_0 més alta, i significa que els homes poden accelerar més ràpid, perllongar la fase d'acceleració i aconseguir velocitats més altes. Els nostres resultats coincideixen amb els de Slawinski et al.[1] tot i que les diferències són molt més grans en el nostre estudi. Dues possibles causes podrien explicar això: 1) les diferències de rendiment entre homes i dones (classificació de la IAAF), i 2) un possible biaix en les dades de Slawinski et al.[1] que van extreure les dades antropomètriques dels corredors en dies diferents a les curses i van aconseguir els temps parcials per mitjà de taules de la IAAF, en què el mètode va anar canviant al llarg dels 30 anys de registres de temps inclosos en l'estudi.

Diverses característiques antropomètriques i estructurals contribueixen al millor rendiment dels homes en l'esprint. Els homes són més alts, tenen les extremitats més llargues, tenen més massa muscular i són més potents que les dones.[20,96,104,105] Com s'ha anat repassant en la tesi, el rendiment en l'esprint està molt lligat a la producció de grans GRFs;[4,7,8,17] el fet de tenir més massa muscular representa un avantatge per als homes a l'hora de produir aquestes forces. Weyand et al.[7,12,17] apunten que el factor limitant més gran de l'esprint és el poc temps de producció de força durant la fase de recolzament. Diversos factors neuromusculars estan relacionats amb la producció de força amb el mínim temps (tipus i longitud de fibra, angles de pennació, sistema nerviós, *stiffness*...), tot i que homes i dones semblen diferir tan sols en l'*stiffness* musculotendinosa.[1,96] Segons sembla, l'*stiffness* dels membres inferiors pot influenciar el rendiment en esprint degut a la importància d'aquest en optimitzar el cicle d'estirament-escurçament.[1,15,107] Aquesta superioritat a l'hora d'aplicar grans quantitats de força en poc temps, sumada al fet que els homes tenen el CM més elevat i les extremitats més llargues, contribueix a una longitud més gran de pas, cosa que afavoreix el rendiment en l'esprint per part dels homes. En aquest sentit, Debaere et al.[20] van estudiar com la longitud i la freqüència de pas afectava el rendiment en homes i dones velocistes en les diferents fases de la carrera (acceleració, màxima velocitat i manteniment). Els seus resultats demostren que les diferències de rendiment entre sexes eren degudes a una longitud de pas superior dels homes en totes les fases de la carrera. A més dels factors antropomètrics i estructurals, estudis sobre fisiologia muscular mostren que les dones tenen menors activitats d'enzims glucolítics i menor CSA de les fibres de tipus II, que també podrien anar en detriment del seu rendiment en l'esprint, comparat amb els homes.[96,104,108]

5.1.3 Propietats mecàniques de l'esprint i rendiment

El temps a recórrer certa distància ha sigut el mètode més utilitzat per mesurar el rendiment en l'esprint degut a la seva senzillesa i fiabilitat.[88,99] No obstant, recentment ha sorgit una nova metodologia basada en el perfil de F-V durant l'esprint i ha proporcionat dades valuosíssimes per individualitzar l'entrenament, així com per avaluar el mateix rendiment.[24,25] Com s'ha explicat, del perfil de F-V se'n poden extreure les SMPs com són: la F_0, la força màxima teòrica que l'atleta pot aplicar al terra en condicions hipotètiques de no velocitat amb un vector anteroposterior; la V_0, la velocitat màxima teòrica en condicions hipotètiques que no hi hagués cap resistència a vèncer; i la P_{max}, la potència màxima extrapolada de la relació F-V. La F_0 està relacionada amb l'acceleració inicial i per tant se la relaciona amb el rendiment en distàncies curtes. En aquest aspecte, Morint et al.[88] proposen que la F_0 es relaciona amb distàncies de 10 m a 20 m en jugadors de futbol i rugbi. Els resultats de les nostres investigacions mostren fortes correlacions amb la F_0 i el rendiment en els 10 m ($r = -0{,}769$; $P < 0{,}001$), però no hem trobat cap més associació entre F_0 i altres distàncies analitzades. En la mateixa línia que els nostres resultats, Marcote-Pequeño et al.[99] també van trobar correlacions fortes entre la F_0 i l'esprint de 20 m analitzant dones futbolistes. En canvi quan la F_0 s'ha relacionat amb distàncies més llargues d'esprint (100 m) no s'han trobat associacions.[1,8,11] De la mateixa manera, Rabita et al.[18] no van trobar correlacions entre la F_0 i el temps en córrer 40 m. Per tant, els resultats trobats en la literatura coincideixen amb els nostres i confirmen que la F_0 està lligada a l'acceleració inicial i és un bon indicador del rendiment en distàncies molt curtes. A més d'això, Morin et al.[8,11] suggereixen que la F_0 és l'única SMP que no mostra diferències entre velocistes de molt alt nivell i velocistes mediocres, coincidint amb els nostres resultats de l'Estudi I.

Pel que fa a la V_0 i a la P_{max}, la literatura mostra uns resultats molt consistents i troba bones correlacions amb les diferents distàncies analitzades. La P_{max} és normalment l'SMP que mostra correlacions més estables en qualsevol distància analitzada (de 20 m a 100 m), mentre que la V_0 sembla més determinant en distàncies més llargues.[1,8,11] Marcote-Pequeño et al.[99] van mostrar correlacions quasi perfectes entre la P_{max} i el temps als 40 m (r = -0,990; $P < 0,01$) i un pèl més dèbils quan correlacionava la V_0 amb la mateixa distància (r = -0,800; $P < 0,01$). En un estudi que analitza les SMPs en velocistes de nivell internacional, Rabita et al.[18] també van trobar correlacions pràcticament perfectes entre la P_{max} (r = 0,932; $P < 0,01$) i el rendiment en els 40 m i fortes amb la V_0 (r = 0,803; $P < 0,01$). En canvi quan la distància augmenta fins als 100 m, la V_0 sembla la propietat mecànica més determinant de cara al rendiment. Després d'analitzar les finals de 100 m de campionats del món, Slawinski et al.[1] van observar que la V_0 (r = -0,900; $P < 0,01$) es correlacionava millor que la P_{max} (r = -0,760; $P < 0,01$) amb els temps dels 100 m llisos. A més, aquest mateix autor suggeria que la P_{max} és el determinant més gran del rendiment en distàncies que van al voltant dels 60 m, en canvi la V_0 passa a ser el determinant més important sobre distàncies de 100 m.[1] De manera similar amb el que s'ha exposat, els resultats obtinguts de les nostres investigacions que correlacionen els temps en 40 m, 80 m i 150 m amb la V_0 (r = -0,967; -0,959; -0,963; $P < 0,001$, respectivament), i amb la P_{max} (r = -0,944; -0,903; -0,865; $P < 0,001$, respectivament) suggereixen que a mesura que augmenta la distància, la V_0 sembla explicar millor el rendiment.

A banda dels estudis correlacionals, els resultats generals d'aquesta tesi donen suport a la idea que la V_0, o la capacitat de produir GRFs horitzontals més grans a altes velocitats, és la variable més important per al rendiment en velocistes.[1,11] Evidentment aquesta afirmació s'ha d'agafar amb cautela, ja que el rendiment d'un velocista és principalment el temps als 100 m o 200 m; si el *gold standard* fossin 40 m, probablement aquestes conclusions serien diferents. Sigui com sigui, en els dos estudis comparatius ha quedat palès que la V_0 era la propietat mecànica que mostrava diferències més grans entre grups, i sempre el grup més ràpid mostrava la V_0 més alta. A més, després dels 5 mesos d'entrenament, els velocistes van millorar el rendiment en totes les distàncies, la V_0 i la D_{RF} (la capacitat de produir GRFs anteroposteriors a mesura que augmenta la velocitat) mentre que la F_0 i la P_{max} van resultar inalterades. Per tant, els nostres resultats se sumen a la literatura que dona suport a la idea que la V_0, o el perfil de F-V orientat cap a la velocitat, és clau per als velocistes.

5.1.4 Adaptacions a l’entrenament d’esprint

Dels resultats del seguiment de l’entrenament d’un grup de velocistes (Estudi III) es va veure que l’SBTM va ser altament efectiu per millorar el rendiment. Amb la intenció que l’estudi fos al màxim d’ecològic, no hi va haver cap tipus d’intervenció, només es va fer el seguiment de l’entrenament i es van portar a terme els tests quan pertocava. A diferència dels Estudis I i II, en aquest estudi es va incloure un espectre més gran de distàncies (10 m, 40 m, 80 m, 150 m, 300 m), ja que la mostra de velocistes d’aquest estudi era bastant heterogènia pel que fa a especialitats atlètiques, que anaven de 100 m a 400 m. Després dels 5 mesos d’entrenament, el rendiment va augmentar significativament en totes les distàncies, encara que no en la mateixa magnitud (Taula 4.3.2, pàg. 122). Curiosament, en la distància més curta, 10 m, és on es van donar les millores més grans (7 %, ES = 1,11; $P < 0.01$). La resta de distàncies presentaren millores molt similars: 40 m (4,9 %; ES = 0,61; $P < 0,01$), 80 m (4,4 %; ES = 0,51; $P < 0,01$), 150 m (4,5 %; ES = 0,46; $P < 0.01$) i 300 m (5,1 %; ES = 0,50; $P < 0,01$). Pel que fa a les SMPs només es van trobar millores en la V_0 (5,3 %; ES = 0,40; $P < 0,01$) i el D_{RF} (7,2 %; ES = 0,91; $P < 0,01$). Ni la F_0 ni la P_{max} van canviar significativament.

No tenim coneixement de cap estudi similar que hagi analitzat velocistes en aquest tipus de condicions i especialment que hagin valorat les SMPs, per tant futures comparacions seran difícils. De totes maneres sorprèn la millora tan gran en el rendiment en els 10 m sense millora de la F_0. Com s’ha explicat, la F_0 és la força màxima teòrica que hom pot aplicar al terra amb una direcció anteroposterior i està estretament relacionada amb l’acceleració inicial.[18,24,115] Encara que part de l’entrenament anés enfocat a millorar l’acceleració, i en efecte va funcionar, atesa la millora en el temps als 10 m, cal remarcar el fet que la F_0 no va canviar durant l’SBTM. D’altra banda, les millores en V_0 i D_{RF} signifiquen que després de l’SBTM els atletes van ser capaços: 1) d’aconseguir velocitats màximes més altes, i 2) d’aplicar la força més efectivament sobre el terra durant tota l’acceleració, amb un vector més horitzontal. En altres paraules, després de l’SBTM, els atletes milloraren la forma en què aplicaven les forces al terra i van orientar el seu perfil de F-V cap a la velocitat. Tot i no poder comparar els resultats, la investigació realitzada per Morin et al.[8,11] confirma que la V_0 i el D_{RF} són les propietats mecàniques més importants per al rendiment d'un velocista, i també les variables que més diferencien velocistes d'elit i mediocres. Així, les millores en 40 m aniran lligades amb la millora del D_{RF} per millora d'acceleració, i les millores en 80 m i 150 m estan directament relacionades amb les millores de la V_0 per millora de velocitat màxima.[8,11,18] Per acabar, les millores en el temps als 300 m no creiem que es puguin atribuir a millores de les SMPs i sí a millores associades a aspectes metabòlics, a la millora de l'economia de carrera i resistència a la fatiga.[116–118]

5.2 Volums musculars de la cuixa i rendiment en esprint

Per tal d'entendre la influència del desenvolupament muscular en el rendiment en l'esprint, o les adaptacions musculars que l'entrenament d'esprint comporta, es discutiran de manera global els resultats dels tres estudis que conformen la present tesi. Primer s'analitzaran les diferències entre població velocista i no velocista, després les diferències entre sexes de velocistes i per últim les adaptacions musculars que tenen lloc després d'un període de 5 mesos d'entrenament d'esprint en velocistes de nivell nacional.

5.2.1 Velocistes vs. no velocistes

Comparant velocistes i població jove molt activa (Estudi I) es va veure que els velocistes presentaven tots els grups musculars de la cuixa més grossos que la població activa, encara que els isquiosurals mostraren ser especialment més grossos que la resta (32 %; ES = 2,11; $P < 0.01$) (Taula 4.1.2, pàg. 83). Adductors (23 %; ES = 1,33; $P < 0,05$) i quàdriceps (14 %; ES = 1,12; $P < 0,05$) també van ser significativament més grossos en el grup de velocistes, tot i que la mesura d'ES indica que les diferències van ser pràcticament la meitat que la dels isquiosurals. És important remarcar que els dos grups no presentaren diferències antropomètriques (Taula 4.1.1, pàg. 82), per tant les diferències en MV no són atribuïbles a diferències en mesures corporals, i sí a diferències en desenvolupament muscular als membres inferiors. Mentre que hi deu haver un component genètic als perfils muscular analitzats,[42] és molt probable que els efectes de l'entrenament contribueixin a les diferències observades i reflecteixin el rol de cada un dels grups musculars en l'esprint.

Observant individualment els músculs isquiosurals, s'identifica una troballa molt interessant: només els tres isquiosurals biarticulars (extensors de maluc i flexors de genoll) presenten diferències significatives entre els grups de velocistes i actius (Taula 4.1.2, pàg. 83). BFlh, ST i SM van ser molt més grossos (ES = 1,85-2,31) en el grup de velocistes, mentre que el BFsh va presentar diferències moderades (ES = 0,96) i no significatives. Aquest descobriment coincideix amb les troballes realitzades per Ema et al.[47] segons les quals, comparant velocistes i no velocistes, només va trobar diferències significatives en els tres isquiosurals biarticulars. Específicament, aquests músculs han mostrat ser crucials en l'esprint i en la producció de forces horitzontals,[70,72,75,76] per tant, les diferències entre velocistes i no velocistes poden estar molt lligades a aquest fet.

De la mateixa manera, quan s'analitzaren individualment els diferents músculs que conformen el quàdriceps, només es trobaren diferències significatives en l'únic múscul biarticular dels quatre, l'RF (Taula 4.1.2, pàg. 83). L'RF participa en l'extensió de genoll i la flexió de maluc, mentre que els vasts (VL, VI i VM) solament produeixen l'extensió de maluc. Durant l'esprint els vasts s'activen al final del *swing* (preactivació) fins gairebé al final de la fase de recolzament, realitzant l'extensió del genoll, i principalment col·laboren en la producció de GRFs verticals.[6,69,70] Altrament, l'RF també està actiu a l'inici i meitat del swing, col·laborant en la flexió del maluc, per tal de reposicionar la cama.[6,70] D'altra banda, Dorn et al.,[69] utilitzant models matemàtics d'activació muscular durant l'esprint, ja van predir grans implicacions de l'RF en lloc dels vasts en la carrera d'alta velocitat. Aquests resultats tornen a coincidir amb les troballes d'Ema et al.[47] que, tal com s'ha explicat abans, comparant velocistes amb no velocistes només va trobar diferències significatives en l'MV de l'RF i no en els vasts.

Tal com s'ha exposat anteriorment, en el cas dels adductors també es trobaren diferències significatives entre grups, encara que no tan acusades com en el cas dels isquiosurals (Taula 4.1.2, pàg. 83). Altra vegada, aquests resultats estan en sintonia amb els d'Ema et al.[47] i Handsfield et al.[42] que, comparant velocistes amb no velocistes, també van trobar l'MV dels adductors significativament més gran en el grup de velocistes. Els adductors són, en efecte, un grup muscular important en l'esprint, i hi ha abundant literatura que ho corrobora.[48,49,70,71] A banda del seu nom, els adductors tenen altres funcions que l'adducció del maluc. L'adductor major és un important extensor de maluc,[79–81] i durant el cicle de l'esprint presenta activitat des del final del swing fins al final de la fase de recolzament.[70,71] A més, la resta de músculs inclosos en el grup dels adductors (adductor llarg, curt i mínim, pectini i gràcil) han demostrat importants funcions en la flexió de maluc,[79–81] i de la mateixa manera mostren activitat des de l'inici fins a la meitat del swing, contribuint a la reposició del membre inferior.[70,71]

5.2.2 Homes vs. dones velocistes

Una vegada comprovades les diferències de volums musculars de la cuixa entre població velocista i població no velocista, vam trobar convenient investigar si hi havia diferències en els MVs entre sexes en velocistes. Els resultats de l'Estudi II s'han d'analitzar amb cura. Agafant els resultats d'MVs absoluts, els nois presentaren músculs molt més grossos que les noies (Taula 4.2.2, pàg. 100), no obstant, aquesta comparació presenta un biaix antropomètric. Tal com es mostra a la Taula 4.2.1 (pàg. 99), els nois eren més alts i pesaven més que les noies. Els MVs estan estretament relacionats amb la llargada del segment i la massa del múscul en qüestió,[42,45] i les mesures dels segments estan relacionades amb l'alçada i la massa del cos humà.[45] Així, cossos més grossos tindran MVs més grans. Per solucionar aquest biaix, es van normalitzar els MVs per l'alçada i la massa, tal com proposa Handsfield et al.[42] Una vegada normalitzats els MVs de la cuixa, velocistes homes i dones només es diferenciaven en els isquiosurals (ES = 1,26; $P < 0{,}05$), mentre que els adductors i els quàdriceps no presentaren diferències (Figura 4.2.2, pàg. 101). Els nostres resultats estan parcialment d'acord amb els de Handsfield et al.[42] que, en analitzar homes i dones velocistes, no van trobar diferències en cap dels tres grups musculars esmentats. Una possible explicació per a aquestes discrepàncies podria estar relacionada amb el nivell de rendiment entre sexes. Mentre que Handsfield no va reportar diferències de rendiment, en el nostre estudi els homes velocistes pertanyien a un nivell de rendiment en esprint notablement superior al de les seves homònimes, tal com es veu reflectit a la classificació de la IAAF (Taula 4.2.1, pàg. 99). En efecte, aquest fet podria ser clau en el cas dels isquiosurals degut a l'importantíssim rol que té aquest grup muscular durant l'esprint.

5.2.3 Volums musculars de la cuixa i rendiment en esprint

Dels resultats de la comparació entre velocistes i no velocistes (Estudi I) es podria entendre que el volum dels isquiosurals, principalment, i dels adductors serien els més importants de la cuixa de cara al rendiment en l'esprint. Si a això se li suma que comparant velocistes nois i noies només es trobaren diferències en l'MV d'isquiosurals, tenint en compte els nivells de rendiment a què pertanyia cada grup, es podria arribar a la precipitada conclusió que, de la cuixa, la mida dels isquiosurals és la més determinant per a l'esprint, o dit d'una altra manera, que com més grossos siguin els isquiosurals millor serà el rendiment en l'esprint. Per arribar a aquesta conclusió no n'hi ha prou a comparar el desenvolupament muscular de velocistes i altres grups. Per això tant a l'Estudi I com a l'Estudi II els diferents MVs es van correlacionar amb els resultats obtinguts dels tests d'esprint. Els resultats dels dos estudis mostren associació dels isquiosurals i els adductors amb el rendiment en esprint i manca d'associació amb els quàdriceps. En l'Estudi I, per exemple, l'MV d'isquiosurals mostra correlacions moderades i fortes amb els diferents indicadors de rendiment en esprint (temps als 10 m, als

40 m, V_0 i P_{max}) (Figura 4.1.3, pàg. 84). De fet, es va trobar una clara tendència a enfortir el grau d'associació a mesura que augmentava la distància de l'esprint. En el temps als 10 m, l'MV dels isquiosurals mostra tendència a associació moderada (r = -0,463; *P* = 0,071), als 40 m es troba una forta associació (r = -0,670; *P* < 0,01), i finalment l'associació amb V_0, representativa de la velocitat màxima, fou encara més forta (r = 0,757; *P* < 0,01). Com s'ha introduït, l'MV dels adductors també va mostrar cert grau d'associació amb el rendiment en esprint, tot i que en menor mesura i amb menys variables de rendiment que els isquiosurals. Específicament, el desenvolupament muscular dels adductors es va associar moderadament amb el temps en 40 m (r = -0,563; *P* < 0,05) i fortament amb la V_0 (r = 0,642; *P* < 0,01).

De la mateixa manera, en l'Estudi II, també es van correlacionar els diferents MVs amb el rendiment en l'esprint. De manera general l'MV dels isquiosurals va mostrar correlacions més fortes amb el rendiment en l'esprint que no pas l'MV dels adductors (Figura 4.2.4, pàg. 104). Les distàncies utilitzades en l'Estudi II (40 m i 80 m) són més representatives del rendiment en velocistes que no pas les de l'Estudi I (10 m i 40 m), per tant aquí només es tindran en compte els temps de l'esprint i no les seves propietats mecàniques. Així, l'MV dels isquiosurals es va relacionar fortament tant amb el temps als 40 m (r = -0,647; *P* < 0,01), com amb el temps en 80 m (r = -0,685; *P* < 0,01). Per contra, l'MV dels adductors va mostrar associacions moderades amb el temps als 40 m (r = -0,514; *P* < 0,05) i amb el temps als 80 m (r = -0,530; *P* < 0,05).

Prenent els resultats obtinguts en l'Estudi I i el II —tant les diferències musculars entre sexes en velocistes i no velocistes com les correlacions d'MVs i rendiment en esprint— es pot arribar a la conclusió que el desenvolupament muscular dels isquiosurals està fortament relacionat amb el rendiment en esprint (en distàncies de 40 m i 80 m). A més també cal remarcar la importància que té l'MV dels adductors en el rendiment, sempre per sota de la dels isquiosurals. Com ja s'ha anat comentant, els isquiosurals han demostrat ser un múscul clau en el rendiment en l'esprint,[70,72,75] a més, hi ha literatura recent que ha trobat que el volum muscular d'isquiosurals és un dels factors diferencials entre velocistes i no velocistes.[42,43,47]

5.2.4 Hipertròfia i entrenament d'esprint

En l'Estudi III es va fer un seguiment d'un grup de velocistes de nivell nacional durant un macrocicle de pista coberta que va durar 5 mesos. L'entrenament dels velocistes va consistir principalment en entrenament específic d'esprint, tot i que també hi va haver una part d'entrenament complementari de força i pliomètric (Figura 4.3.3, pàg. 120). Els resultats del seguiment mostren que les millores en l'esprint van estar acompanyades d'una hipertròfia significativa en la musculatura de la cuixa. Durant el període d'entrenament els quàdriceps van augmentar un 6 % (ES = 0,41; P < 0,01), els isquiosurals un 10 % (ES = 0,62; P < 0,01) i els adductors un 12 % (ES = 0,87; P < 0,01). Tot i que no podem demostrar aquest fet, creiem que l'augment més acusat en isquiosurals i adductors, comparats amb el quàdriceps, pot tenir relació amb la major participació d'aquests grups musculars en l'esprint. Val a dir que els atletes també van fer entrenament de força, encara que sense finalitats purament hipertròfiques, i l'entrenament de força sembla la forma més efectiva d'induir el creixement muscular,[27,119] per tant, és fàcil pressuposar que l'entrenament de força realitzat pels atletes hagués tingut certa influència sobre el creixement muscular. De tota manera, quan analitzem els exercicis que es van dur a terme durant el macrocicle, veiem que els atletes van fer molts més exercicis dominants de genoll, o dit d'una altra manera, que incideixen més sobre el quàdriceps, que no dominants de maluc, que incideixen més sobre isquiosurals i/o adductors. Aquest fet sumat a la gran especificitat d'entrenament d'esprint que regia el període d'entrenament dels atletes fa pensar que les diferències hipertròfiques de quàdriceps respecte a isquiosurals i adductors van ser degudes a les implicacions musculars que tenen aquests grups musculars en l'esprint. No tenim coneixement de cap treball que hagi estudiat la hipertròfia, a nivell macroscòpic, de quàdriceps, isquiosurals i adductors després d'un període d'entrenament d'esprint. En una revisió sobre adaptacions musculars en l'entrenament d'esprint, Ross et al.[28] suggereixen que per induir la hipertròfia amb entrenament d'esprint es necessiten un mínim de 8 setmanes. És important aclarir que les seves conclusions es basen només en tres treballs realitzats amb cicloergòmetre i la quantificació de la hipertròfia a nivell fibril·lar, i sempre del vast extern; per tant, les comparacions resulten, com a mínim, complicades. De manera similar, Cadefau et al.[29] van investigar l'efecte que tenien 8 mesos d'entrenament específic d'esprint en atletes joves. Tot i que tant el tipus d'entrenament com la durada del període presenten moltes similituds amb el nostre treball, les comparacions es fan difícils, ja que en el seu treball, Cadefau et al.[29] van analitzar només el diàmetre de fibres del vast extern, sense tenir en compte els altres músculs, i a més, la mostra analitzada la componien atletes molt joves, els quals presenten un potencial adaptatiu molt diferent.

Una troballa destacable de l'Estudi III va ser el curs temporal del procés hipertròfic, amb un creixement molt accentuat durant la primera meitat del període d'entrenament, i un manteniment durant la segona meitat (Taula 4.3.2, pàg. 122, i Figura 4.3.4, pàg. 124). Segons el nostre entendre, dues possibles raons poden ser la causa d'aquesta dinàmica: 1) el procés de desentrenament dels atletes abans de començar el macrocicle (acabaven de passar 6 setmanes de descans total); i 2) els volums d'entrenament relativament més alts de la primera meitat del període d'entrenament (Figura 4.3.3, pàg. 120). Sembla que la velocitat més alta de degradació de proteïna contràctil té lloc a les 2-3 setmanes de començar el període de desentrenament.[28] En la revisió d'adaptacions musculars a l'entrenament d'esprint, Ross et al.[28] reporten que hi ha una pèrdua del 5 % al 13 % de massa muscular durant períodes de 2 a 7 setmanes després del cessament de l'entrenament. Per tant és lògic pensar que els atletes, després de 6 setmanes de descans, havien perdut les adaptacions morfològiques i estructurals aconseguides la temporada anterior. D'altra banda, Bruusgard et al.[111] han demostrat que el múscul adquireix nous mionuclis després d'un procés d'entrenament, els quals no es perden després d'un període de desentrenament, i per tant atròfia. Aquest manteniment dels nous mionuclis accelera els futurs processos hipertròfics i explica que els individus que prèviament han estat molt entrenats, quan són reentrenats, guanyen massa muscular més fàcilment.[111,112] A més de tot això, està bastant assumit que el volum d'entrenament és un dels factors més importants per a l'augment de massa muscular.[113,119] Per tant, tenint en compte que el grup de velocistes analitzats eren atletes altament entrenats, que començaven el procés desentrenats i havent perdut part de les adaptacions musculars i que durant el primer període d’entrenament van estar sotmesos a volums més alts d’entrenament, s’entén que el gran augment de massa muscular es donés durant la primera meitat del macrocicle.

6 CONCLUSIONS

6.1 Conclusions

Hamstrings muscularity is related to sprint performance, especially at maximal velocities. Over sprint distances where maximal velocity is key, the muscularity of the hamstrings is more important. Therefore, greater hamstrings MV should lead to a better sprint performance, over 40 m and up to 100m.

Muscularity of the adductor muscle group also seems important for sprint performance, however, to a lesser degree than hamstrings.

V_0, the ability to produce high anteroposterior GRF at high speeds or having a "velocity-oriented" F-V profile is the main determinant SMP of performance in sprinters, and one of the differential factors between fast and slow sprinters.

After 5 months of sprint training, MVs of quadriceps, hamstrings and adductors increased significantly, especially during the first month of training. Moreover, the relatively higher hypertrophic changes of hamstrings and adductors, compared to quadriceps, might be related to the prominent role of these muscle groups in sprinting.

6.2 Practical applications

Findings from this study and the growing body of research related to hamstring musculature highlight the need for practitioners to focus on appropriate training for hamstring development. Nevertheless, it must be noted that correlations and linear regressions do not imply "cause and effect", thus focusing on increasing the muscularity of hamstrings alone will probably not translate to improved performance.

Sprinting is a very complex motor pattern and it requires highly specific strategies for training. Sprint-specific training (i.e., weighted sled sprinting, sprint technique drills, sprinting itself…) is vital and the most crucial stimulus to improve sprint performance. However, regarding complementary training, coaches and practitioners should incorporate unilateral complex exercises that imitate sprinting action, overloading the hamstrings while working on the triple extension action.

Special attention should be paid to adductor muscle group training, besides hip adduction, due to its importance in sprint performance. Movements in the sagittal plane such as hip extension and hip flexion exercises also target the adductor muscles and are performed during sprinting.

Due to large differences found in sprinters' RF, we believe that sprint complementary training should also target hip flexors muscle groups. Hip flexors are often forgotten in sprint training, and we encourage coaches and sprinters to focus on specific training of these muscle groups as well.

6.3 Limitations

Despite the evidence, it must be noted that the findings from this thesis are limited to thigh muscularity, therefore, a broader view of whole lower limb muscularity would give a better understanding of its influence in sprint performance. Future research could possibly target the study of gluteal, iliopsoas and gastrocnemius muscularity in order to improve understanding of the whole picture.

The biggest limitation of the present thesis is the small sample size of each study. It is not easy to recruit elite and sub-elite athletes for research and especially more difficult for training studies, and this is the main reason of the limited sample size used herein. Due to this small sample size, the correlational analysis were performed using pooled data as recommended. However, bigger samples allow to perform stratified analysis which are more representative of each population.

Another limitation is that in Study III, we did not test the athletes at the end of the preceding season, thus we do not know the exact magnitude of the detraining. Despite having the empirical knowledge, for future research we recommend testing the athletes before starting the detraining period.

Finally, the conclusions of this thesis are limited to highly trained Caucasian sprinters and possible transference to other ethnicities or populations (team sports athletes) are yet to be elucidated.

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