Year : 2015

ÉVALUATION ET PRISE EN CHARGE DES RISQUES DE BLESSURE DES ISCHIO-JAMBIERS CHEZ LE SPRINTEUR

GUEX Kenny

UNIL | Université de Lausanne
Faculté de biologie et de médecine

Institut des Sciences du Sport
Département de Physiologie

ÉVALUATION ET PRISE EN CHARGE DES RISQUES DE BLESSURE DES ISCHIO-JAMBIERS CHEZ LE SPRINTEUR

Thèse de doctorat ès sciences de la vie (PhD)

Présentée à la

Faculté de biologie et de médecine
De l'Université de Lausanne

par

Kenny GUEX

Master of Science en sciences du mouvement et du sport, UNIGE, Genève
Bachelor of Science HES-SO en physiothérapie, HECVSanté, Lausanne

Jury

Prof. Brigitte Jolles-Haeberli, Présidente
Prof. Grégoire Millet, Directeur de thèse
Dr. Gerald Gremion, co-Directeur de thèse
Prof. Olivier Deriaz, expert
Dr. Pierre-Etienne Fournier, expert

Lausanne, février 2015

UNIL | Université de Lausanne
Faculté de biologie
et de médecine

Ecole Doctorale
Doctorat ès sciences de la vie

Imprimatur

Vu le rapport présenté par le jury d'examen, composé de

Président	Madame Prof. Brigitte **Jolles-Haeberli**
Directeur de thèse	Monsieur Prof. Grégoire **Millet**
Co-directeur de thèse	Monsieur Dr Gerald **Gremion**
Experts	Monsieur Dr Pierre-Etienne **Fournier**
	Monsieur Prof. Olivier **Deriaz**

le Conseil de Faculté autorise l'impression de la thèse de

Monsieur Kenny Guex

Master of Science de l'Université de Genève

intitulée

EVALUATION ET PRISE EN CHARGE DES RISQUES DE BLESSURE DES ISCHIO-JAMBIERS CHEZ LE SPRINTEUR

Lausanne, le 1 avril 2015

pour La Doyenne
de la Faculté de Biologie et de Médecine

Prof. Brigitte Jolles-Haeberli

« Quand on ne sait pas, on ne se pose pas trop de questions, mais quand on commence à disposer d'un début d'explication, on veut à tout prix tout savoir, tout comprendre. »

Bernard Werber

Remerciements

En premier lieu, je tiens à remercier chaleureusement mon Directeur de thèse, le Prof. Grégoire Millet, qui a su me guider avec pertinence tout en me laissant suffisamment de place pour me développer de manière autonome. Sa passion contagieuse pour la recherche, sa disponibilité et sa rigueur sont autant d'éléments qui m'ont permis de m'épanouir durant ce long processus.

Je remercie sincèrement la Haute Ecole de Santé Vaud, et tout particulièrement Mmes Mireille Clerc et Pascale Damidot, de m'avoir permis de réaliser cette thèse dans les meilleures conditions. Je me mesure la chance que j'ai eue de bénéficier de ce cadre de travail et de ce temps et je vous en suis extrêmement reconnaissant.

Mes remerciements vont ensuite à tous les membres de mon jury de thèse pour le temps qu'ils ont consacré au suivi de ce travail ainsi que pour leurs remarques constructives.

Je remercie aussi particulièrement mon co-Directeur, le Dr. Gerald Gremion, ainsi que M. Jean Lambert de m'avoir offert l'accès à leurs locaux et à leur matériel lors de mes différentes investigations.

Un grand merci à tous les sujets ayant donné de leur temps, de leur force et de leur sueur lors de mes différentes recherches.

Je suis également très reconnaissant envers tous mes collègues qui ont pris le temps de partager avec moi leurs connaissances cliniques et scientifiques.

Je tiens à remercier ma compagne, Noémie, qui a toujours cru en moi. Merci de ton soutien, de tes encouragements et de ton amour.

Finalement, je dédie cette thèse à mes parents. Merci d'avoir toujours tout mis en œuvre avec enthousiasme pour que je puisse atteindre mes objectifs personnels.

Liste des publications

En lien avec la thèse

Article 1 – Guex, K., Fourchet, F., Loepelt, H., & Millet, G. P. (2012). Passive knee-extension test to measure hamstring tightness: influence of gravity correction. *Journal of Sport Rehabilitation, 21*(3), 231-234.

Article 2 – Guex, K., Daucourt, C., & Borloz, S. (2014). Validity and Reliability of Maximal Strength Assessment of Knee Flexors and Extensors Using Elastic Bands. *Journal of Sport Rehabilitation,* Epub ahead of print.

Article 3 – Guex, K., Gojanovic, B., & Millet, G. P. (2012). Influence of hip-flexion angle on hamstrings isokinetic activity in sprinters. *Journal of Athletic Training, 47*(4), 390-395.

Article 4 – Guex, K., Degache, F., Gremion, G., & Millet, G. P. (2013). Effect of hip flexion angle on hamstring optimum length after a single set of concentric contractions. *Journal of sports sciences, 31*(14), 1545-1552.

Article 5 – Guex, K., & Millet, G. P. (2013). Conceptual Framework for Strengthening Exercises to Prevent Hamstring Strains. *Sports medicine, 43*(12), 1207-1215.

Article 6 – Guex, K., Lugrin, V., Borloz, S., & Millet, G. P. (2014). Influence of a 6-weeks eccentric training on hamstring functional parameters and injury incidence in sprinters during a winter season. Soumis.

Hors thèse (par date)

Degache, F., Morin, J. B., Oehen, L., Guex, K., Giardini, G., Schena F., Millet, G. Y., & Millet, G. P. (2014). Anticipatory adaptations in running mechanics during the World's most challenging mountain ultra-marathon. Soumis.

Degache, F., Van Zaen, J., Oehen, L., Guex, K., Trabucchi, P., & Millet, G. (2014). Alterations in Postural Control during the World's Most Challenging Mountain Ultra-Marathon. *PLoS One, 9*(1), e84554.

Degache, F., Guex, K., Fourchet, F., Morin, J. B., Millet, G. P., Tomazin, K., & Millet, G. Y. (2013). Changes in running mechanics and spring-mass behaviour induced by a 5-hour hilly running bout. *J Sports Sci, 31*(3), 299-304.

Fourchet, F., Millet, G. P., Tomazin, K., Guex, K., Nosaka, K., Edouard, P., Degache, F., & Millet, G. Y. (2012). Effects of a 5-h hilly running on ankle plantar and dorsal flexor force and fatigability. *Eur J Appl Physiol, 112*(7), 2645-2652.

Guex, K. (2012). Kinematic Analysis of the Women's 400m Hurdles. *New Studies in Athletics, 27*(1/2), 41-51.

Résumé

La déchirure des ischio-jambiers est la blessure non-traumatique la plus fréquemment rencontrée dans les sports demandant une course à haute vitesse. Les ischio-jambiers sont particulièrement vulnérables lors de la fin de phase d'oscillation du sprint étant donné qu'ils se contractent excentriquement alors qu'ils sont en position d'allongement. Le renforcement excentrique a été montré comme étant une méthode efficace pour diminuer le risque de blessure. Cependant, les exercices classiquement utilisés comme le *Nordic hamstring* ne soumettent pas les ischio-jambiers à un niveau d'allongement spécifique au sprint. Dès lors, l'objectif de cette thèse était d'évaluer le fonctionnement des ischio-jambiers à différents niveaux d'allongement musculo-tendineux puis de transposer dans la pratique les résultats obtenus afin de concevoir des exercices plus spécifiques aux besoins des athlètes. Avant cela, une première partie avait pour but de proposer de nouvelles méthodes d'évaluation de terrain des ischio-jambiers. Les différents travaux réalisés pour cette thèse ont permis : 1) de proposer deux nouveaux outils de terrain pour l'évaluation de la flexibilité et de la force des ischio-jambiers ; 2) de montrer que le niveau d'allongement influence directement la force produite par les ischio-jambiers et de suggérer que ce niveau d'allongement semble être un stimulus au moins aussi déterminant que le mode de contraction musculaire pour générer des adaptations de l'architecture musculaire propices à la diminution du risque de blessure ; 3) de proposer des modalités spécifiques de renforcement des ischio-jambiers destinées aux sprinteurs dans une perspective de prévention des blessures et de montrer l'efficacité de ces recommandations sur l'amélioration d'un certain nombre de facteurs de risque de blessure. Finalement, ce travail a ouvert de nouvelles perspectives allant de la proposition d'exercices de renforcement de terrain au développement d'un système motorisé spécifique au sprint permettant le renforcement et l'évaluation de la force des ischio-jambiers en passant par différents projets de recherche.

Abstract

High-speed running sports accounts for the majority of hamstring strains. The terminal swing phase of the running cycle is believed to be the most hazardous as the hamstrings are undergoing an active lengthening contraction in a long muscle length position. Prevention-based strength training relies mainly on eccentric exercises. However, most hamstrings exercises like the Nordic hamstring are performed at an inadequately low hip-flexion angle. Thus, the objective of this thesis was to assess the hamstring function at different muscle lengths and depending on the obtained results to design strength exercises more specific to the athlete's need. Before that, a first part of this thesis aimed to develop new assessment methods of the hamstring on site. The different studies included in the present thesis allowed: 1) to propose two new methods to test the hamstring flexibility and strength on the field; 2) to show that the hamstring muscle length directly influences its level of strength, and to suggest that the training range of motion could be a dominant stimulus (as important than contraction type) for modifying the muscle architecture, which leads to a decrease in hamstring injury risk; 3) to define sprint specific parameters for prevention-based strength training, and to show the efficiency of these recommendations on the improvement of several injury risk factors for the hamstring. Finally, this thesis proposed new perspectives: 1) new strength exercises on site; 2) the development of a motorised device specific for the sprint which could be used to strength and to assess the hamstring; 3) several future research projects.

Table des matières

Chapitre 1. Introduction

1.1. Préambule

La déchirure des ischio-jambiers est la blessure non-traumatique la plus fréquemment rencontrée dans les courses de sprint et les sauts en athlétisme (Alonso et al., 2012), en football (Hagglund et al., 2013), rugby (Brooks et al., 2005), football américain (Feeley et al., 2008), football australien (Orchard et al., 2013), ainsi qu'en football gaélique (Murphy et al., 2012). La course à haute vitesse (c.-à-d., le sprint) – le point commun entre ces différents sports – est responsable de la majorité des lésions des ischio-jambiers recensée dans ces activités (Brooks et al., 2006; Drezner et al., 2005; Elliott et al., 2011; Murphy et al., 2012; Woods et al., 2004).

Suite à une déchirure des ischio-jambiers, le sportif blessé est écarté des terrains durant une longue période. Cela a pour conséquence, en plus de la diminution de ses performances, de générer des pertes financières importantes pour les clubs. Par exemple, lors de la saison 1999-2000, parmi tous les clubs professionnels de football en Angleterre la perte financière due aux blessures était estimée à plus de 100 mio CHF (Woods et al., 2002). La déchirure des ischio-jambiers représentant 12% de toutes les blessures retrouvées dans ce championnat (Woods et al., 2004), il apparait primordial de se pencher sur sa prévention. Afin d'optimiser cette dernière, il faut, dans un premier temps, comprendre le fonctionnement des ischio-jambiers ainsi que les caractéristiques biomécaniques responsables de cette blessure lors de la course.

1.2. Anatomie des ischio-jambiers

Les ischio-jambiers sont un groupe musculaire de la région fémorale postérieure constitué d'un muscle latéral : le biceps fémoral (formé d'un chef court et d'un chef long) et de deux muscles médiaux : le semi-tendineux et le semi-membraneux (Figure 1). Tous ces muscles (à l'exception du chef court du biceps fémoral) ont une insertion proximale au niveau de l'ischion et une insertion distale au niveau du segment jambier. Ce sont donc des muscles bi-articulaires ayant une action à la fois sur l'articulation de la hanche et sur celle du genou. Une autre caractéristique générale de ce groupe musculaire est de posséder une plus grande proportion (51 à 58%) de fibres de type II que de fibres de type I (Dahmane et al., 2006; Garrett et al., 1984).

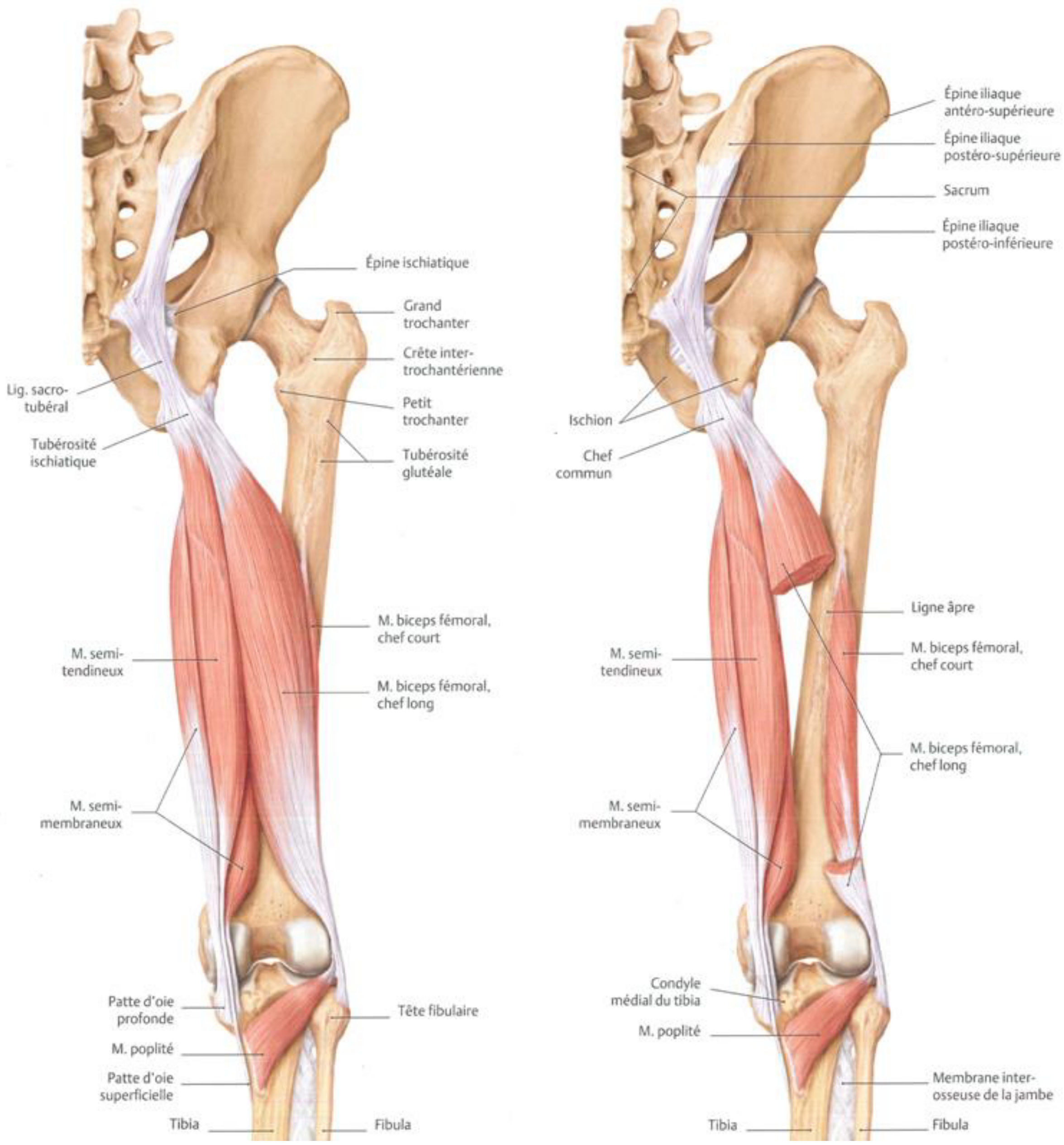


Figure 1. Vue postérieure de la cuisse (Schünke et al., 2006).

1.2.1. Biceps fémoral

Proximalement, le chef long s'insère au niveau de la tubérosité ischiatique et du ligament sacro-tubéral par le biais d'un tendon commun avec le semi-tendineux. Le chef court s'insère sur la lèvre latérale de la ligne âpre au tiers moyen du fémur. Distalement, le chef long et le chef court sont réunis et s'insèrent sur la tête de la fibula. Le chef long a la morphologie d'un muscle uni-penné avec ses fibres arrangées en parallèle, alors que le chef court à la forme d'un trapèze oblique avec des fibres longues sur le côté proximal et des fibres courtes sur le côté distal (Kumazaki et al., 2012) (Figure 2). Le chef long est innervé par le nerf tibial, alors que le nerf fibulaire commun innerve le chef court (Schünke et al., 2006).

Le chef long est bi-articulaire. Il a donc une action à la fois sur l'articulation de la hanche et du genou. Au niveau de la hanche, il est extenseur (principalement lorsque le genou est en extension). Il assure la stabilisation du bassin dans le plan sagittal et il est rétroverseur de ce dernier. Au niveau du genou, il est fléchisseur et rotateur latéral de la jambe lorsque le genou est fléchi. Le court chef est mono-articulaire. Il agit donc uniquement au niveau du genou en tant que fléchisseur (Schünke et al., 2006).

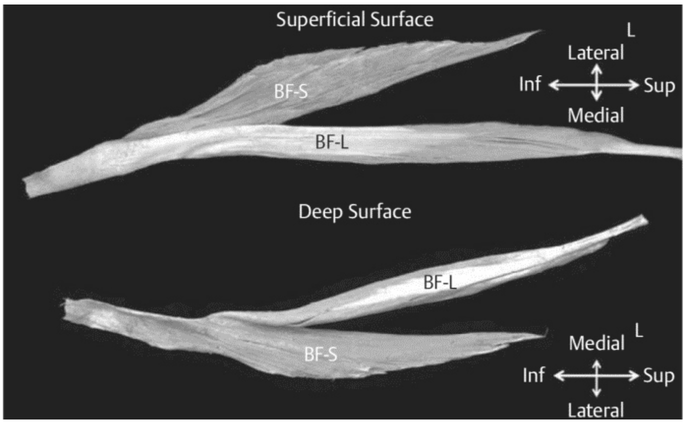


Figure 2. Morphologie du biceps fémoral. BF-S, chef court du biceps fémoral ; BF-L, chef long du biceps fémoral (Kumazaki et al., 2012).

1.2.2. Semi-tendineux

Il s'insère proximalement au niveau de la tubérosité ischiatique et du ligament sacro-tubéral par le biais d'un tendon commun avec le chef long du biceps fémoral. Distalement, il s'insère sur la face médiale du tibia au niveau de la patte d'oie superficielle. Le semi-tendineux est un muscle fusiforme avec des fibres longitudinales (Kumazaki et al., 2012) (Figure 3). Il est innervé par le nerf tibial (Schünke et al., 2006).

Au niveau de la hanche, le semi-tendineux est extenseur (principalement lorsque le genou est en extension). Il assure la stabilisation du bassin dans le plan sagittal et il est rétroverseur de ce dernier. Au niveau du genou, il est fléchisseur et rotateur médial de la jambe lorsque le genou est fléchi (Schünke et al., 2006).

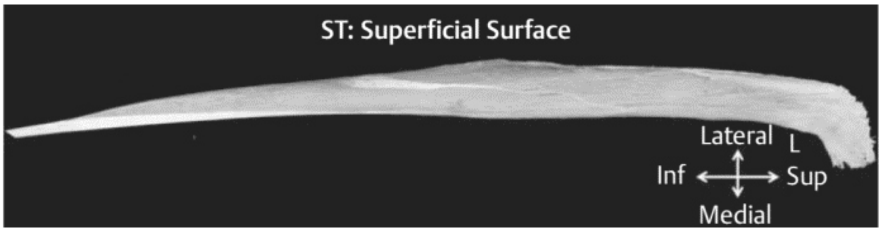


Figure 3. Morphologie du semi-tendineux. ST, semi-tendineux (Kumazaki et al., 2012).

1.2.3. Semi-membraneux

Proximalement, il s'insère au niveau de la tubérosité ischiatique, latéralement au tendon commun du chef long du biceps fémoral et du semi-tendineux. Il se divise distalement en trois parties. La première s'insère au niveau du condyle médial du tibia. La seconde sur le fascia du muscle poplité. Enfin, la troisième partie va vers la face postérieure de la capsule pour former le ligament poplité oblique. Cette division en trois parties correspond à la patte d'oie profonde. Le semi-membraneux a la morphologie d'un muscle uni-penné avec ses fibres arrangées en parallèle (Kumazaki et al., 2012) (Figure 4). Il est innervé par le nerf tibial (Schünke et al., 2006).

Au niveau de la hanche, le semi-membraneux est extenseur (principalement lorsque le genou est en extension). Il assure la stabilisation du bassin dans le plan sagittal et il est rétroverseur de ce dernier. Au niveau du genou, il est fléchisseur et rotateur médial de la jambe lorsque le genou est fléchi (Schünke et al., 2006).

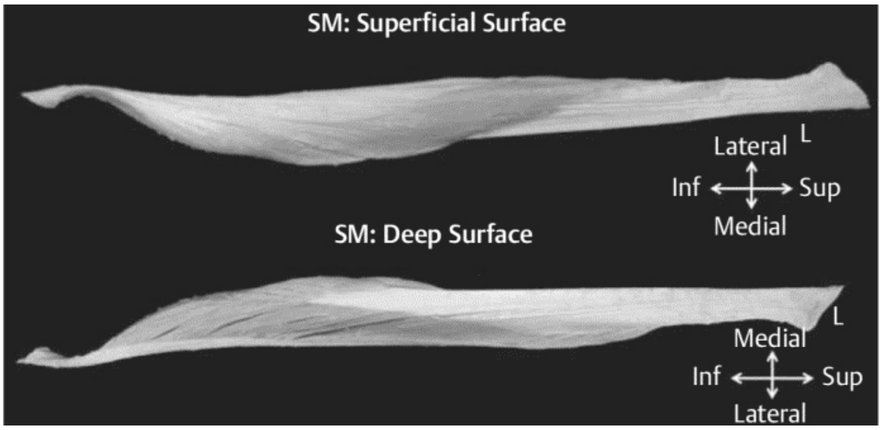


Figure 4. Morphologie du semi-membraneux. SM, semi-membraneux (Kumazaki et al., 2012).

1.3. Biomécanique du sprint

1.3.1. Généralités

Le cycle de course commence avec le contact initial au sol de l'avant du pied (*touchdown*, 0%) et se termine lorsque ce même pied entre à nouveau en contact avec le sol (100%) (Figure 5). Par opposition à la marche, en sprint (et plus généralement en course) il n'y a pas de phase de double appui ; le cycle de course est composé uniquement d'une phase d'appui suivie d'une phase d'oscillation. Le décollement du pied (*toe off*) marque le passage d'une phase à l'autre. Les sprinteurs de classe mondiale ont une phase d'appui correspondant à 22% du cycle de course

(Mann et al., 1980). Elle peut être divisée en deux parties : l'absorption et la génération d'énergie. Lors de l'absorption, le quadriceps et le triceps sural se contractent excentriquement pour absorber le choc du contact au sol alors que les extenseurs de hanche (c.-à-d., le grand fessier et les ischio-jambiers) ont une activité concentrique. Lors de la génération d'énergie, le quadriceps et le triceps sural s'activent concentriquement pour permettre la propulsion du corps vers l'avant. Durant cette phase d'appui, la hanche passe d'une position de flexion à une position d'extension d'environ 20°, alors que le genou passe d'une position de flexion d'environ 45° lors de l'absorption à une flexion de 25° en fin de propulsion (Novacheck, 1998).

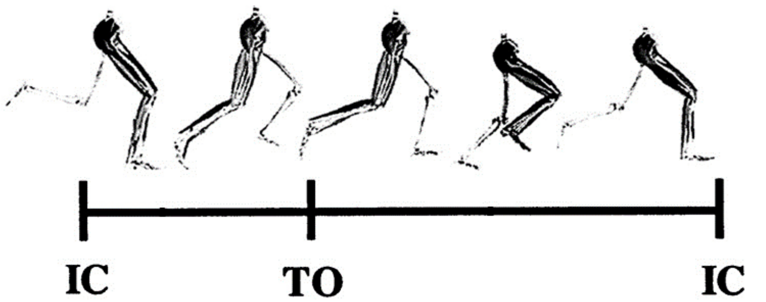


Figure 5. La phase d'appui du cycle de course va du contact initial (*touchdown*) au *toe off*. La phase d'oscillation du *toe off* au contact initial du même pied. IC, contact initial ; TO, *toe off* (Novacheck, 1998).

La phase d'oscillation peut être divisée en deux parties. Lors de la première, la hanche passe d'une position d'extension à une position de flexion grâce à l'activité concentrique des fléchisseurs de hanche. La flexion du genou est augmentée de manière passive jusqu'à environ 130°. Lors de la fin de la phase d'oscillation, la hanche s'étend et la flexion du genou diminue jusqu' à moins de 30° afin de préparer la phase d'appui (Novacheck, 1998).

1.3.2. Biomécanique du sprint et ischio-jambiers

De par leur nature bi-articulaire, les ischio-jambiers sont constamment soumis à des modifications d'allongement lors du sprint. Plusieurs explorations tridimensionnelles du sprint ont observé un pic d'allongement des ischio-jambiers lors de la fin de phase d'oscillation du cycle de course (Chumanov et al., 2007; Higashihara et al., 2014; Schache et al., 2012; Thelen et al., 2005; Yu et al., 2008) (Figure 6). A ce moment, l'augmentation de l'allongement du semi-membraneux, du semi-tendineux et du chef long du biceps fémoral atteint respectivement 10%, 9% et 12% de plus par rapport à leurs longueurs en position debout statique (Schache et al., 2012).

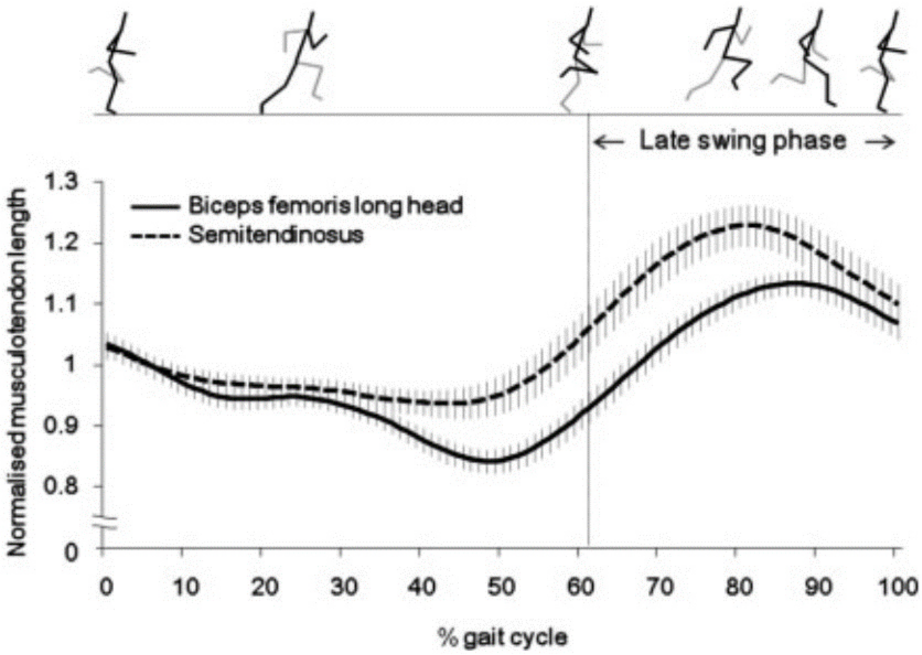


Figure 6. Allongement des ischio-jambiers lors du sprint. Le pic d'allongement est atteint durant la fin de phase d'oscillation (Higashihara et al., 2014).

Cet allongement important des ischio-jambiers est dû à la combinaison d'une flexion de hanche importante et d'une flexion relativement faible du genou lors de la fin de phase d'oscillation. En effet, la hanche atteint son pic de flexion entre 75% et 80% du cycle de course avec une flexion pouvant aller jusqu'à 90° selon les études (Nagano et al., 2014; Thelen et al., 2005). A 85% du cycle de course, lors de l'allongement maximal des ischio-jambiers, la hanche est toujours fléchie entre 60° et 70°. Elle s'étend ensuite progressivement jusqu'à 45° de flexion avant le contact initial. Le genou s'étend, lui, depuis une position de 130° à environ 55% du cycle de course jusqu'à près de 20° de flexion après 95% du cycle (Nagano et al., 2014; Thelen et al., 2005) (Figure 7).

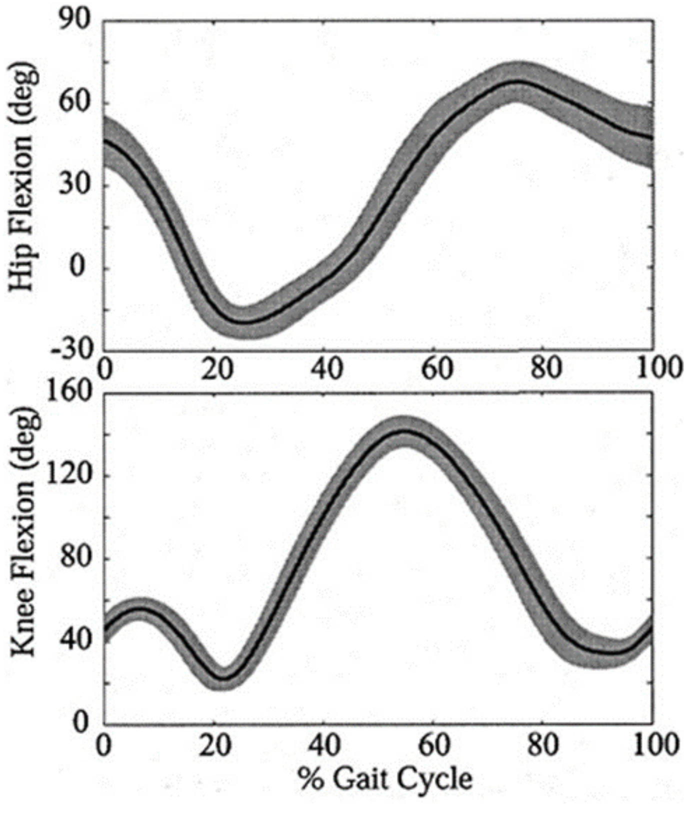


Figure 7. Evolution des angles de hanche et de genou lors du sprint (Thelen et al., 2005).

Lors de la seconde partie de la phase d'oscillation la tension est d'autant plus importante sur les ischio-jambiers que la hanche controlatérale est en position d'extension. Ceci a pour effet de limiter la rétroversion du bassin, ce qui aurait diminué l'allongement des ischio-jambiers en rapprochant leurs insertions proximales de leurs insertions distales. De manière générale, durant tout le cycle de course, le bassin n'oscille que de manière négligeable autour de sa position angulaire (Schache et al., 2002).

Lors du sprint à vitesse maximale, l'augmentation de la longueur des ischio-jambiers retrouvée lors de la fin de phase d'oscillation se fait à haute vitesse. Ceci est dû à l'ouverture du genou qui s'étend à plus de 1000°/s (Kivi et al., 2002). Cette extension rapide du genou impose aux ischio-jambiers de se contracter excentriquement afin de freiner l'avancée du segment jambier vers l'avant. Lors de la phase d'appui, ils assurent ensuite l'extension de la hanche et se contractent donc concentriquement. Cependant, Yu et al. (2008) ont également identifié une contraction excentrique des ischio-jambiers lors de la fin de la phase d'appui. Les mesures effectuées par électromyographie de surface (EMG) lors du sprint montrent qu'ils ne sont pas actifs lors de la première partie de la phase d'oscillation qui amène le genou à une flexion d'environ 130°. C'est à partir des deux tiers du cycle de course (c.-à-d., en fin d'oscillation) qu'ils sont activés, et ceci jusqu'à la fin du premier tiers du cycle suivant (c.-à-d., en fin d'appui) (Jonhagen et al., 1996; Pinniger et al., 2000; Yu et al., 2008) (Figure 8).

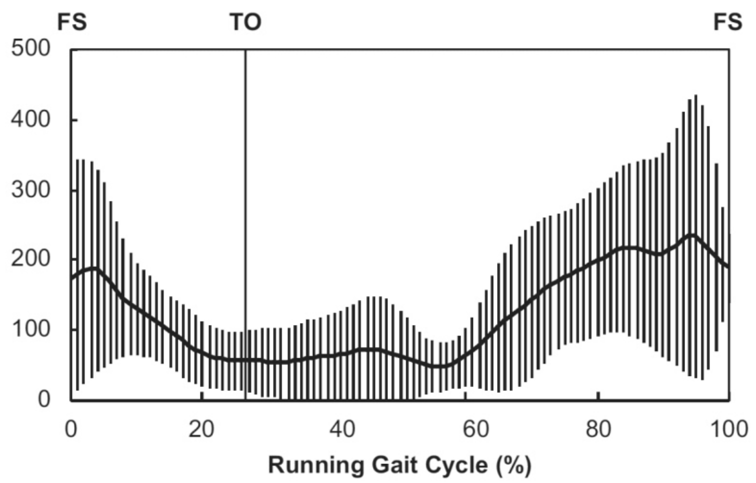


Figure 8. Activité EMG du chef long du biceps fémoral lors du cycle de course (Yu et al., 2008).

La contraction excentrique retrouvée lors de la fin d'oscillation s'intensifie avec la vitesse du sprint. En effet, Chumanov et al. (2007) ont montré que le pic de force du complexe musculo-tendineux des ischio-jambiers passait de 36 N/kg lors d'un sprint à 80% de la vitesse maximale à 52 N/kg lors d'un sprint à vitesse maximale. Ce pic de force serait 50% supérieur à la force maximale isométrique des ischio-jambiers (Sun et al., 2014). Les auteurs s'accordent sur le fait qu'il serait retrouvé lors de la fin de phase d'oscillation environ au même moment que le pic d'allongement (Higashihara et al., 2014; Schache et al., 2012; Sun et al., 2014). En revanche, il y a débat sur la présence d'un second pic de force lors de la phase d'appui. En effet, pour Sun et al. (2014), les ischio-jambiers atteindraient également un pic de force lors de la partie initiale de la phase d'appui avec des valeurs 40% supérieures à leur force maximale isométrique. Cependant, ce résultat n'est pas partagé par d'autres auteurs (Higashihara et al., 2014; Schache et al., 2012).

Finalement, lors du sprint, les ischio-jambiers ont – à l'image du triceps sural – une fonction de stockage et de restitution d'énergie élastique demandant aux tendons sollicités d'opérer à des niveaux élevés de contrainte et d'allongement (Hogervorst et al., 2014). Durant la phase d'appui, ils contribuent au transfert de puissance de la hanche vers le genou et permettent ainsi un déplacement horizontal efficace du centre de masse vers l'avant. Par conséquent, une blessure des ischio-jambiers entraînera une diminution de la force horizontale lors de l'appui (Mendiguchia et al., 2014).

1.4. Blessures des ischio-jambiers

Les blessures musculo-tendineuses des ischio-jambiers sont dues, en général, à un traumatisme direct ou indirect. Les traumatismes directs, comme par exemple les coups, entraînent des contusions. Les traumatismes indirects sont liés à une altération de l'intensité ou de la synergie de la contraction (Agre, 1985). Cela peut engendrer plusieurs degrés de blessure allant de la contracture (c.-à-d., une contraction involontaire d'un certain nombre de fibres sans lésion anatomique) à la déchirure (c.-à-d., une lésion au niveau de la fibre ou du muscle dans son ensemble) en passant par l'élongation (c.-à-d., un étirement anormal de la fibre entraînant une lésion myofibrillaire) (Danowski et al., 2005).

1.4.1. Incidence

En athlétisme, avec 16 à 26% de toutes les blessures recensées, la déchirure des ischio-jambiers est le diagnostic le plus fréquemment posé (Alonso et al., 2012; Drezner et al., 2005). Elle survient principalement lors des épreuves de sprint. Une incidence de 20% par an a d'ailleurs été retrouvée chez des sprinters japonais (Sugiura et al., 2008). En football, la déchirure des ischio-jambiers représente 12% de toutes les blessures (Ekstrand et al., 2011; Woods et al., 2004). Durant les saisons 1997-1998 et 1998-1999 cela représentait, parmi tous les clubs professionnels anglais, 15 matchs manqués par club par saison. Chaque club ayant subi, en moyenne, cinq déchirures par saison (Woods et al., 2004). En rugby, en dehors des hématomes de la cuisse dus aux coups, la déchirure des ischio-jambiers est la blessure la plus fréquemment retrouvée en match (15% des blessures) (Brooks et al., 2005). En football américain, elle représente la lésion la plus fréquente (12% des blessures du système musculo-squelettique) (Feeley et al., 2008). En football australien, elle est également la blessure la plus communément retrouvée (15% des blessures) et entraîne, en moyenne, 21 matchs manqués par club par saison. Chaque club étant touché, en moyenne, par six déchirures chaque saison (Orchard et al., 2013). En football gaélique, la déchirure des ischio-jambiers est aussi la lésion la plus fréquente (24% des blessures) (Murphy et al., 2012). Enfin, en baseball, elle représente la seconde cause d'absence chez les joueurs de terrain (14% des blessures) (Posner et al., 2011).

1.4.2. Mécanisme lésionnel

Les déchirures des ischio-jambiers recensées dans ces différents sports surviennent, dans la majeure partie des cas (57 à 74%), lors de la course à haute vitesse (Brooks et al., 2006; Drezner et al., 2005; Elliott et al., 2011; Murphy et al., 2012; Woods et al., 2004) (Figure 9). Pour Askling et al. (2012; 2007a), la course à haute vitesse représente le premier type de blessure des ischio-jambiers. Ces mêmes auteurs décrivent un second type de blessure lors duquel les ischio-jambiers se déchirent durant des mouvements d'allongement extrêmes (p. ex., stretching, shoot en hauteur, tacle) (Askling et al., 2012; Askling et al., 2007b) (Figure 9). La localisation de la lésion semble ne pas être la même selon que la blessure soit de type course à haute vitesse ou de type étirement.

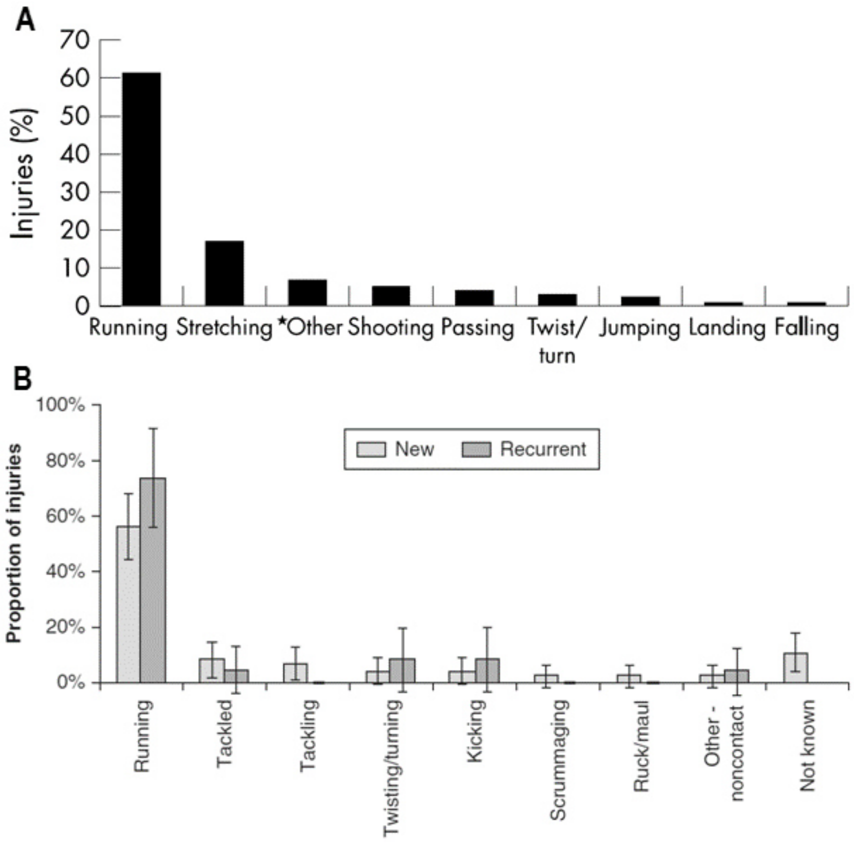


Figure 9. Causes de déchirure des ischio-jambiers en football (A) (Woods et al., 2004) et en rugby (B) (Brooks et al., 2006).

Lors d'une lésion de type course à haute vitesse, la fin de phase d'oscillation et la phase d'appui correspondent aux deux périodes durant lesquelles la déchirure des ischio-jambiers est susceptible de survenir (Chumanov et al., 2012; Higashihara et al., 2014; Orchard, 2012; Sun et al., 2014; Yu et al., 2008). Cependant, pour plusieurs raisons, la fin de phase d'oscillation est considérée comme la phase la plus à risque. Premièrement, durant cette phase, entre 75% et 85% du cycle de course, les ischio-jambiers atteignent leur pic de force alors qu'ils se contractent excentriquement pour freiner l'ouverture du segment jambier (Higashihara et al., 2014; Schache et al., 2012). Si ce type de contraction est répété, il a la particularité de générer des dommages au niveau du muscle (Wood et al., 1993). Ensuite, l'amplitude de l'allongement d'un muscle a été montrée comme étant le facteur déterminant dans la survenue des déchirures musculaires (Garrett et al., 1987). Or, durant la fin d'oscillation, la combinaison de la flexion de hanche et de l'extension du genou induit un allongement important des ischio-jambiers (Figure 6). Il a été montré qu'à environ 85% du cycle de course le chef long du biceps fémoral, le semi-tendineux et le semi-membraneux sont allongés de respectivement 12%, 9% et 10% de plus que leur longueur de repos (Schache et al., 2012). Finalement, une étude de cas (Schache et al., 2009) a rapporté des données biomécaniques au moment de la déchirure des ischio-jambiers d'un athlète qui incriminent la fin de phase d'oscillation. Ensemble, ces données mettent en cause la fin de phase d'oscillation plutôt que la phase d'appui.

Malgré tout, la phase d'appui pourrait également être responsable de lésions des ischio-jambiers. En effet, il a récemment été rapporté que ces derniers atteignaient également un pic de force lors de la phase d'appui initiale (Sun et al., 2014). De plus, lors de la seconde partie de la phase d'appui, il semblerait qu'ils se contractent aussi excentriquement (Yu et al., 2008). Ces données pourraient soutenir le fait que les ischio-jambiers soient également susceptibles de se léser lors de la phase d'appui.

Contrairement à la déchirure des ischio-jambiers de type course à haute vitesse, la déchirure de type étirement n'est pas associée à une contraction excentrique. Elle est provoquée par un étirement extrême des ischio-jambiers, c.-à-d. par une flexion de hanche importante associée à une extension du genou (Askling et al., 2007b). Elle est moins fréquemment retrouvée que la blessure de type course à haute vitesse dans les sports collectifs ou en athlétisme. Cependant, des activités comme le stretching, un shoot en hauteur ou un tacle peuvent tout de même mener à ce type de déchirure (Askling et al., 2012).

1.4.3. Localisation

Une étude (Koulouris et al., 2003) portant sur 179 cas de déchirure des ischio-jambiers chez des sportifs d'élite (footballeurs, athlètes, joueurs de cricket), a montré que 86% des lésions touchent le corps musculaire d'un des ischio-jambiers, 12% un tendon et/ou une insertion proximale et 2% un tendon distal. Parmi les blessures du corps musculaire, 80% concernent le chef long du biceps fémoral, 14% le semi-membraneux et 6% le semi-tendineux. Parmi les lésions localisées au niveau du biceps fémoral, 61% touchent une des deux jonctions myotendineuses, 35% l'épimysium et 4% sont situées à un niveau intramusculaire.

Dans une étude (Askling et al., 2007a) portant sur 18 cas de déchirure des ischio-jambiers chez des sprinteurs, les jonctions myotendineuses proximales (67%) et distales (33%) du chef long du biceps fémoral représentent les principaux sites de blessure. La jonction myotendineuse proximale du chef long du biceps fémoral est donc le site le plus fréquemment touché par la déchirure des ischio-jambiers de type course à haute vitesse (Figure 10, A). Lors de la lésion de type étirement, la déchirure est typiquement localisée à proximité de la tubérosité ischiatique et touche, dans 87% des cas, la partie tendineuse du semi-membraneux (Askling et al., 2007b) (Figure 10, B).

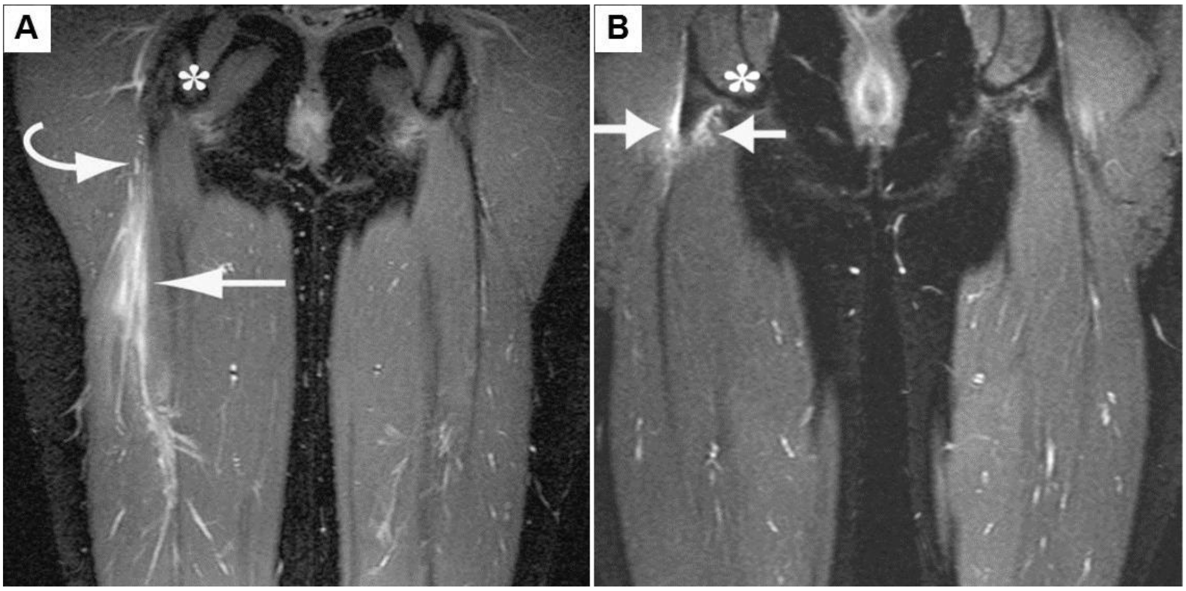


Figure 10. A, lésion de type course à haute vitesse touchant la jonction myotendineuse proximale (flèche droite) et le tendon proximal (flèche incurvée) du chef long du biceps fémoral (Askling et al., 2007a). B, lésion de type étirement touchant le tendon proximal (flèches droites) du semi-membraneux (Askling et al., 2007b).

1.4.4. Facteurs de risque

Un certain nombre de facteurs de risque modifiables et non-modifiables de déchirure des ischio-jambiers a été recensé par différentes revues (Clark, 2008; Liu et al., 2012; Opar et al., 2012; Turner et al., 2014; van Beijsterveldt et al., 2012) et revues systématiques (Freckleton et al., 2013) récentes de la littérature. Il est important de relever que peu de ces facteurs de risque font l'unanimité parmi les différentes études scientifiques sur la question et qu'une association de plusieurs facteurs de risque augmentera d'autant plus le risque de blessure.

Les facteurs de risque non-modifiables suivants sont proposés : l'augmentation de l'âge, l'existence d'une déchirure préalable, l'ethnie aborigène ou africaine, ou certaines caractéristiques anatomiques des ischio-jambiers comme la proportion importante en fibres rapides et la double innervation du biceps fémoral. L'augmentation de l'âge et l'existence d'une déchirure préalable semblent être les facteurs de risque non-modifiables les plus en lien avec l'augmentation du risque de blessure (Freckleton et al., 2013). En effet, il a été retrouvé que chaque année d'âge augmente le risque de déchirure des ischio-jambiers de 1.3 fois en football australien (Verrall et al., 2001) et de 1.8 fois en football (Henderson et al., 2010). Par ailleurs, chez le footballeur professionnel, une déchirure des ischio-jambiers augmente de près de 12 fois le risque de récidive lors de la saison suivante (Hagglund et al., 2006).

Plusieurs facteurs de risque modifiables ont également été mis en avant par ces mêmes revues (Clark, 2008; Freckleton et al., 2013; Liu et al., 2012; Opar et al., 2012; Turner et al., 2014; van Beijsterveldt et al., 2012) ainsi que par une étude portant sur l'anatomie et la physiologie des blessures des ischio-jambiers (Kumazaki et al., 2012) et une étude récente sur la biomécanique du sprint (Lenhart et al., 2014) : un manque de force, une asymétrie bilatérale, un ratio diminué entre la force des ischio-jambiers et celle du quadriceps, une diminution de la longueur optimale (c.-à-d., les ischio-jambiers développent leur force maximale à une longueur musculaire raccourcie), une diminution de la flexibilité, un échauffement insuffisant, la fatigue, un poids de corps trop important ou certaines caractéristiques anatomiques comme l'angle de pennation important et la faible longueur des fibres musculaires du chef long du biceps fémoral et du semi-membraneux comparé à celle du chef court du biceps fémoral et du semi-tendineux. Tous ces paramètres ne restent, cependant, que des risques potentiels. En effet, des résultats contradictoires ressortent des différentes études ayant cherché à identifier les facteurs de risque modifiables de blessure des ischio-jambiers (van Beijsterveldt et al., 2012).

Malgré tout, nombre de travaux ont montré un lien entre ces paramètres et un risque accru de blessure. Par exemple, il a été montré que, par rapport à un muscle partiellement activé, un muscle stimulé dans son intégralité supporte une tension supérieure avant de subir des lésions (Garrett et al., 1987). Il peut ainsi être déduit qu'un muscle plus fort apporterait une meilleure protection contre les blessures et qu'un muscle plus faible risquerait plus de se déchirer (Garrett et al., 1987). En ce qui concerne l'asymétrie bilatérale, une différence de force des ischio-jambiers supérieure à 10% entre les deux jambes est proposée comme un prédicteur de blessure en football américain et en athlétisme (Burkett, 1970; Heiser et al., 1984). En football et en football australien, des différences de respectivement 15% et 8% ont été identifiées comme augmentant le risque de déchirure (Croisier et al., 2008; Orchard et al., 1997). Au sujet du ratio agoniste sur antagoniste chez des footballeurs, un déséquilibre (c.-à-d., des ratios conventionnels et fonctionnels inférieurs à respectivement 0.45-0.47 et 0.80-0.89 selon le dynamomètre utilisé) entre la force des ischio-jambiers et celle du quadriceps est associée à un risque significativement plus élevé de blessure des ischio-jambiers (Croisier et al., 2008). Une diminution de la longueur optimale des ischio-jambiers pourrait également augmenter le risque de blessure. En effet, les athlètes et les joueurs de football australien ayant un angle de genou augmenté lors du pic de force concentrique de leurs ischio-jambiers – donc ayant une longueur optimale des ischio-jambiers diminuée – ont un risque augmenté de blessure (Brockett et al., 2004) (Figure 11). Ceci est lié au fait que, lors de la fin de phase d'oscillation du sprint, leurs ischio-jambiers sont principalement actifs sur la pente descendante de la relation tension-longueur, ce qui les rend plus vulnérables aux lésions (Lynn et al., 1998). Au sujet de la flexibilité, un certain nombre d'études a pu montrer un lien entre une diminution de la souplesse des ischio-jambiers et une augmentation du risque de déchirure (Bradley et al., 2007; Henderson et al., 2010; Witvrouw et al., 2003). Concernant les caractéristiques anatomiques des ischio-jambiers, l'architecture semi-pennée du chef long du biceps fémoral et du semi-membraneux pourrait expliquer pourquoi ces deux muscles sont les principaux sites de lésion lors des déchirures de type course à haute vitesse ou de type étirement (Kumazaki et al., 2012). En effet, en raison de leur angle de pennation, les fibres musculaires du chef long du biceps fémoral et du semi-membraneux sont deux à trois fois plus étirées que celles du chef court du biceps fémoral et du semi-tendineux lorsque le genou s'étend. Elles sont ainsi rendues vulnérables par cet allongement extrême. Finalement, en ce qui concerne la biomécanique de course, il a récemment été montré que la charge imposée aux ischio-jambiers lors de la fin de phase d'oscillation est augmentée lorsque, pour une même vitesse de sprint, la fréquence de pas est augmentée (Lenhart et al., 2014). Ainsi, une technique de course plus basée sur l'amplitude des pas et moins sur la fréquence permettrait de diminuer la contrainte imposée aux ischio-jambiers.

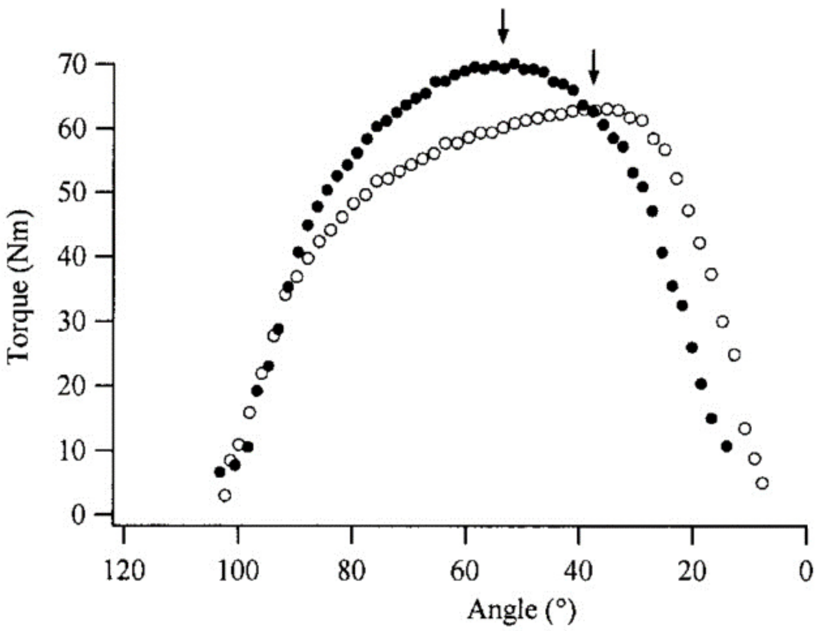


Figure 11. Relation tension-longueur des ischio-jambiers d'un athlète. Les flèches représentent l'angle optimal. En noir, le côté précédemment lésé. Le pic de force est obtenu à un angle de flexion de genou plus important (c.-à-d., à une longueur musculaire plus faible) (Brockett et al., 2004).

1.5. Prévention

Plusieurs études cliniques (Arnason et al., 2008; Askling et al., 2003; Brooks et al., 2006; Gabbe et al., 2006; Petersen et al., 2011; Seagrave et al., 2014) ont évalué les effets de l'inclusion d'un programme de renforcement excentrique dans l'entraînement de footballeurs, de rugbymen, de footballeurs australiens ou de joueurs de baseball sur l'incidence des déchirures des ischio-jambiers. Toutes ces études ont trouvé une diminution comprise entre 60% et 70% de cette incidence chez les sportifs ayant intégré un programme de renforcement excentrique par rapport à ceux ne l'ayant pas intégré. Afin de réaliser l'entraînement excentrique, ces études ont utilisé le *YoYo™ flywheel ergometer* (Askling et al., 2003) (Figure 12, A), ou, dans la majeure partie des cas, le *Nordic hamstring* (Arnason et al., 2008; Brooks et al., 2006; Gabbe et al., 2006; Petersen et al., 2011; Seagrave et al., 2014) (Figure 12, B). Ces deux exercices demandent au sportif de freiner l'extension du genou par un travail excentrique des ischio-jambiers.

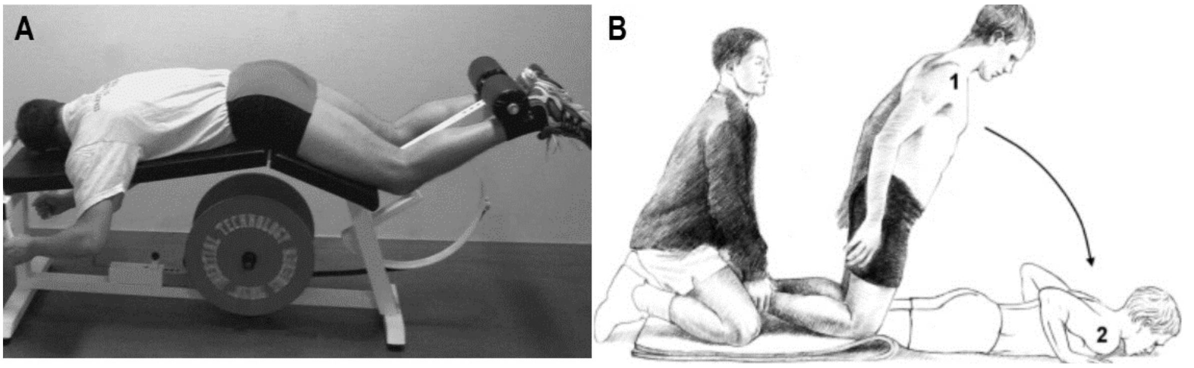


Figure 12. A, *YoYo™ flywheel ergometer* (Askling et al., 2003) ; B, *Nordic hamstring* (Arnason et al., 2008).

La diminution de l'incidence des déchirures des ischio-jambiers observée dans ces études peut être expliquée par l'amélioration d'un certain nombre de facteurs de risque (cf., 1.4.4. Facteurs de risque). Tout d'abord, ces exercices de renforcement excentrique permettent d'améliorer la force des ischio-jambiers (Iga et al., 2012; Kilgallon et al., 2007; Mjolsnes et al., 2004; Potier et al., 2009) et, par conséquent, le ratio entre la force des ischio-jambiers et du quadriceps. En effet, après deux à trois séances par semaine de *Nordic hamstring* durant dix semaines une augmentation de 11% du ratio fonctionnel (de 0.89 à 0.98) a, par exemple, été mesurée (Mjolsnes et al., 2004). Ensuite, ces exercices excentriques permettraient, selon plusieurs études, de modifier l'angle optimal des ischio-jambiers vers une position plus allongée (Brockett et al., 2001; Brughelli, Mendiguchia, et al., 2010; Clark et al., 2005; Kilgallon et al., 2007; Martínez-Ruiz et al., 2014; Potier et al., 2009). Une augmentation de la longueur des fibres musculaires (sans modification de l'angle de pennation) générée par une augmentation du nombre de sarcomères en série serait à l'origine de cette modification de l'angle optimal retrouvée après un programme excentrique (Blazevich et al., 2007; Potier et al., 2009; Seynnes et al., 2007).

1.5.1. Principaux exercices de renforcement des ischio-jambiers

Il existe plusieurs exercices et appareils de fitness permettant un renforcement excentrique des ischio-jambiers. Les principaux exercices utilisés dans le domaine du sport sont présentés ci-dessous.

Lying hamstring curl & seated hamstring curl

Ces deux exercices sont réalisés sur des appareils de fitness. Lors du *lying hamstring curl* (Figure 13, A), les ischio-jambiers sont activés par le biais de leur action au niveau du genou. Les hanches sont à 0° voire 30° de flexion selon les appareils. Afin de mettre l'accent sur la phase excentrique du mouvement, la phase concentrique peut être réalisée à deux jambes et la phase excentrique à une seule. Il est également possible de se faire aider par une autre personne lors de la phase concentrique. Finalement, des dispositifs comme le *YoYo™ flywheel ergometer* (Figure 12, A) permettent d'augmenter la charge lors de la phase excentrique du mouvement. Le *seated hamstring curl* (Figure 13, B) est une variante du *lying hamstring curl*. L'activité des ischio-jambiers au niveau du genou est comparable. Cependant, les hanches sont placées à 90° de flexion. Les ischio-jambiers sont donc principalement activés sur la pente descendante de la relation tension-longueur alors qu'ils travaillent principalement sur la pente ascendante lors du *lying hamstring curl*.

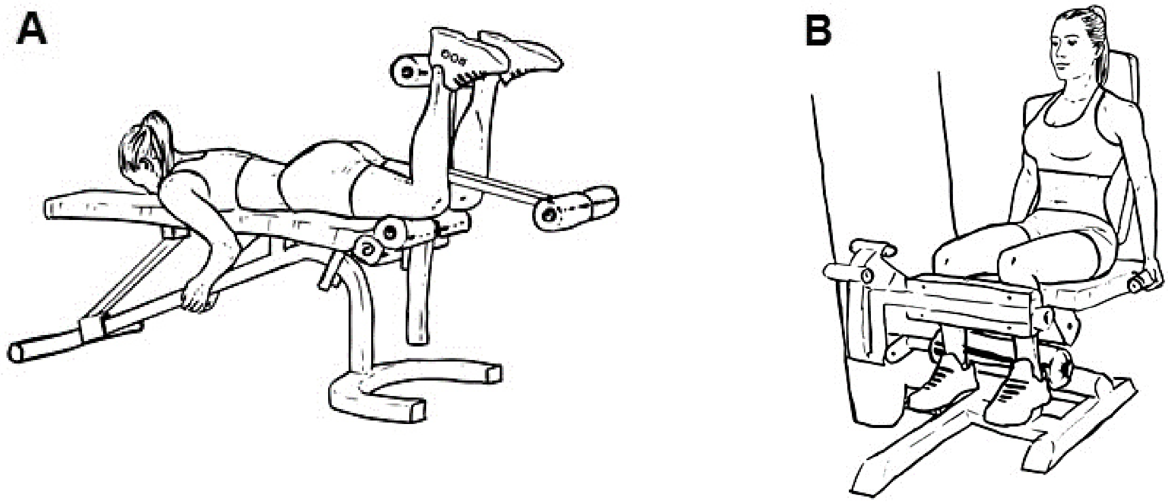


Figure 13. A, *lying hamstring curl* ; B, *seated hamstring curl* (www.workoutlabs.com).

Good morning, Romanian deadlift & single leg deadlift

Ces trois exercices nécessitent une barre olympique d'haltérophilie. Le sujet est debout, les pieds au sol, et tient une barre d'haltérophilie sur les épaules (*good morning* ; Figure 14, A) ou devant lui (R*omanian deadlift* ; Figure 14, B). En position de départ, les genoux sont tendus ou légèrement fléchis. L'exercice consiste à freiner une flexion du tronc puis à remonter en position de départ. Pour cet exercice le dos doit être verrouillé. Ainsi la flexion se fait au niveau des hanches et est freinée par l'activité excentrique des ischio-jambiers. L'aide d'une autre personne lors de la phase concentrique est nécessaire afin de mettre l'accent sur la phase excentrique. Le *single leg deadlift* correspond au même exercice que le R*omanian deadlift* mais réalisé sur une seule jambe (Figure 14, C).

Figure 14. A, *Good morning* (www.workoutlabs.com) ; B, *Romanian deadlift* (Brughelli et al., 2008); C, *Single leg deadlift* (Brughelli et al., 2008).

Nordic hamstring

La réalisation du *Nordic hamstring* (Figure 12, B) ne nécessite aucun matériel hormis un moyen pour fixer les chevilles (p. ex., un espalier ou l'aide d'une autre personne). En position de départ, le sujet est à genoux (à environ 90° de flexion), les hanches en position neutre de flexion/extension. L'exercice consiste à freiner la chute du corps en avant. Une fois les genoux tendus, le retour est réalisé à l'aide des membres supérieurs.

La différence d'activité EMG des ischio-jambiers lors du *lying hamstring curl*, du *good morning*, du *Romanian deadlift* et du *Nordic hamstring* a récemment été investiguée (McAllister et al., 2014). Il en ressort que le *Romanian deadlift* et le *good morning* entraînent l'activité EMG la plus importante. En revanche, le *lying hamstring curl* est l'exercice qui engendre l'activité EMG la plus faible. Lors de ces quatre exercices, les ischio-jambiers médiaux (c.-à-d., le semi-tendineux et le semi-membraneux) ont une activité EMG supérieure à celle du biceps fémoral.

1.6. Problématique

La question de la prévention des blessures des ischio-jambiers chez le sportif est un sujet largement documenté dans la littérature scientifique actuelle. Particulièrement depuis le début des années 2000 et l'apparition du *Nordic hamstring* qui a été utilisé dans la majorité des études sur le sujet. Cependant, malgré une attention marquée pour cette question, il semble que la proportion de déchirure des ischio-jambiers n'ait pas diminué dans des sports comme le football, le rugby ou le football australien (Brooks et al., 2006; Ekstrand & Gillquist, 1983; Ekstrand, Gillquist, et al., 1983; Ekstrand et al., 2011; Orchard et al., 2002; Seward et al., 1993; Woods et al., 2004).

La spécificité des exercices de renforcement est primordiale afin d'améliorer la prise en charge préventive des athlètes réalisant des courses à haute vitesse dans leur sport. Comme précédemment décrit (cf., 1.4.2. Mécanisme lésionnel), la fin de phase d'oscillation est considérée comme la phase la plus susceptible d'engendrer une lésion des ischio-jambiers lors du sprint. Lors de cette phase les ischio-jambiers se contractent excentriquement dans une position d'allongement musculaire importante (c.-à-d., en flexion de hanche importante associée à une faible flexion de genou). Or, les exercices de renforcement utilisés dans les études de prévention (cf., 1.5. Prévention) ne sont pas spécifiques au sprint puisqu'ils n'incluent aucune flexion de hanche (*Nordic hamstring*) ou au mieux une flexion insuffisante (*YoYo*^{TM} *flywheel ergometer*). Ils n'imposent donc pas d'allongement spécifique aux ischio-jambiers. Cette question de l'allongement spécifique des ischio-jambiers lors du renforcement est donc au centre de cette thèse.

1.7. Objectifs de la thèse

La présente thèse expose six études réalisées entre 2010 et 2014. Ces travaux de recherche portent tous sur les ischio-jambiers et sont organisés, dans ce document, en trois parties distinctes (deux articles par partie) (Figure 15). La première s'intéresse aux outils de mesures de terrain utilisés pour évaluer l'extensibilité et la force des ischio-jambiers (Articles 1 & 2). La seconde se focalise sur le fonctionnement des ischio-jambiers à différents niveaux d'allongement musculo-tendineux (Articles 3 & 4). Enfin, la troisième partie porte sur la transposition dans la pratique des résultats obtenus dans la seconde partie afin de concevoir des exercices plus spécifiques aux besoins des athlètes (Articles 5 & 6).

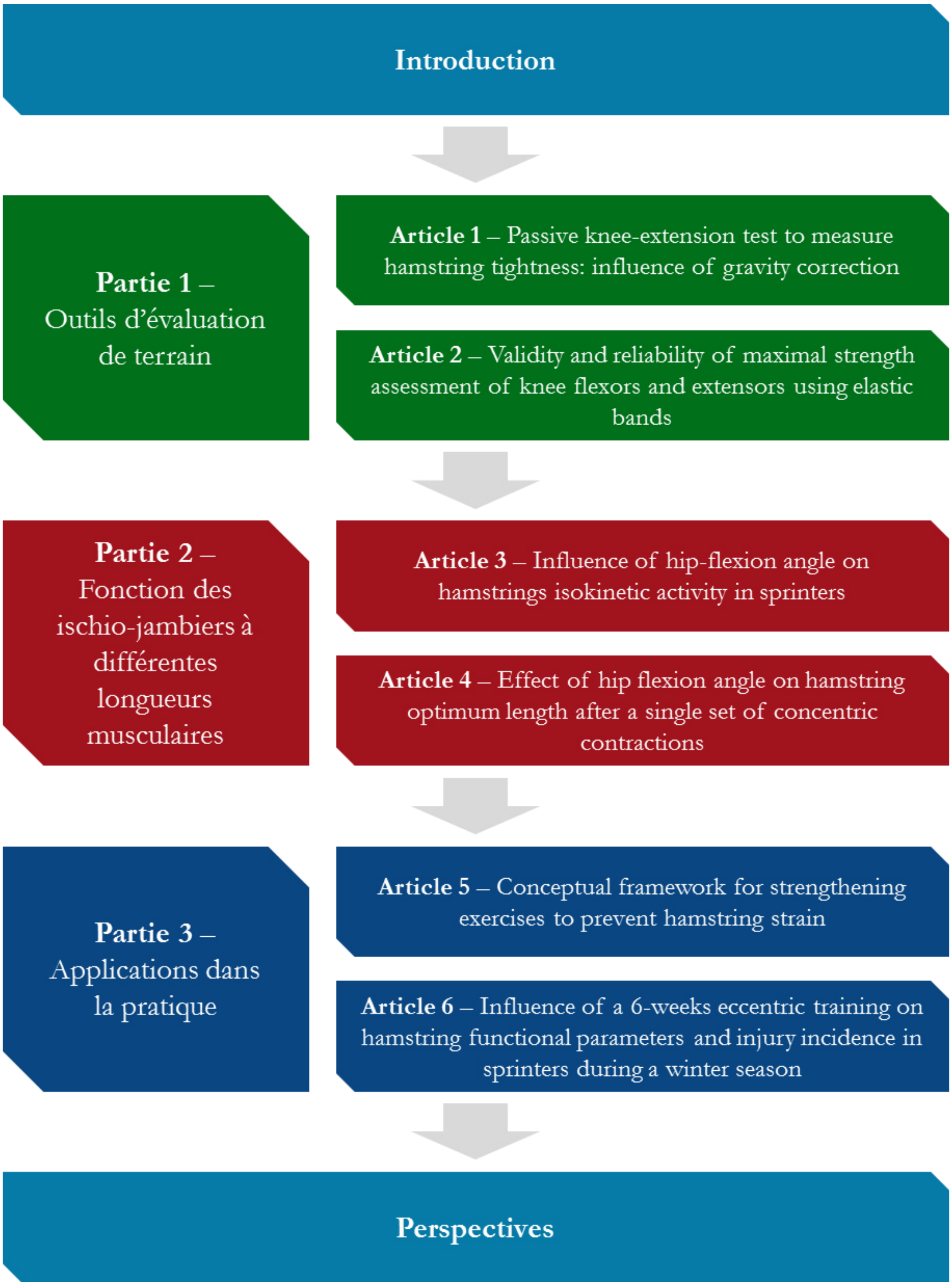


Figure 15. Organisation des différentes études réalisées lors de la thèse

1.7.1. Partie 1 – Outils d'évaluation de terrain

Cette première partie avait pour objectif général de proposer de nouvelles méthodes d'évaluation de deux facteurs de risque de blessure des ischio-jambiers : la flexibilité et la force.

L'objectif de l'Article 1 était de proposer une modification du *passive knee extension test* qui est un test d'extensibilité des ischio-jambiers fréquemment utilisé, mais ayant la limite de ne pas prendre en compte l'effet de la gravité sur le segment jambier testé. Ceci est un problème particulièrement lors de l'évaluation d'athlètes ayant des morphologies différentes (p. ex., lanceurs de poids versus demi-fondeurs) ou lors du suivi d'athlètes sujets à des modifications de masse corporelle (p. ex., des athlètes en phase de croissance ou suivant un programme de musculation).

L'objectif de l'Article 2 était d'évaluer la validité et la fiabilité d'une méthode d'évaluation de la force maximale des ischio-jambiers et du quadriceps réalisée à l'aide de bandes élastiques. Les athlètes et particulièrement les sportifs amateurs n'ont pas systématiquement accès à du matériel de fitness pour s'entraîner. Les bandes élastiques sont couramment utilisées pour du renforcement général ou lors de la rééducation après blessure. Cependant, elles pourraient également être utilisées pour l'entraînement de force à proprement dit. Ceci pour autant qu'en amont la force maximale puisse être évaluée de manière valide et fiable à l'aide de ces mêmes bandes élastiques.

1.7.2. Partie 2 – Fonction des ischio-jambiers à différentes longueurs musculaires

L'objectif général de cette seconde partie était de mieux comprendre comment différents paramètres des ischio-jambiers comme la force, l'activité EMG, l'angle optimal et la fatigabilité sont influencés lorsque le complexe musculo-tendineux des ischio-jambiers est placé, par le biais de différentes flexions de hanche, à différents niveaux d'allongement plus ou moins spécifiques au sprint.

L'Article 3 avait pour objectif d'évaluer l'influence de quatre positions de flexion de hanche (0°, 30°, 60° et 90°) sur la force et l'activité EMG des ischio-jambiers et du quadriceps en isométrique, concentrique et excentrique. Une meilleure compréhension de l'influence de la flexion de hanche sur la force des ischio-jambiers permettrait de mieux sélectionner les exercices de renforcement et également de contrôler et d'ajuster la position des sportifs lors de l'évaluation de la force.

L'objectif de l'Article 4 était de tester l'influence de la flexion de hanche (0° versus 80°) sur l'angle optimal des ischio-jambiers au début et à la fin de 30 répétitions concentriques maximales. La fatigue engendrée par cet exercice a également été monitorée afin de voir si les ischio-jambiers sont aussi fatigables dans les deux positions. L'angle optimal des ischio-jambiers est connu pour être modifié vers une position d'allongement plus importante à la suite d'une séance unique de renforcement excentrique (Brockett et al., 2001). De la même manière, dans cette étude, il était attendu que l'angle optimal des ischio-jambiers soit modifié vers une position d'allongement plus importante à la suite des 30 répétitions concentriques réalisées à 80° de flexion de hanche et qu'aucune modification n'ait lieu à 0°.

1.7.3. Partie 3 – Applications dans la pratique

Cette dernière partie avait pour objectif général de proposer une réflexion structurée pour optimiser les exercices de renforcement des ischio-jambiers puis d'appliquer ces recommandations sur des sprinteurs.

L'Article 5 avait pour objectif de spécifier le choix des paramètres (c.-à-d., le mode de contraction, la charge, l'amplitude, la vitesse, la réalisation uni- ou bilatérale des exercices, le type de chaîne cinétique) des exercices de renforcement des ischio-jambiers dans une perspective de prévention des blessures.

L'objectif de l'Article 6 était de tester les effets d'un entraînement spécifique des ischio-jambiers sur certains facteurs de risque comme la force, les ratios, l'angle optimal et la flexibilité. De plus, un suivi des blessures a été effectué mais sans pour autant pouvoir en tirer des conclusions en raison du faible échantillon d'athlètes inclus dans l'étude.

Chapitre 2. Synthèse des résultats de recherche

2.1. Partie 1 – Outils d'évaluation de terrain

2.1.1. Article 1 – Passive knee-extension test to measure hamstring tightness: influence of gravity correction

Cette première étude (Guex, Fourchet, et al., 2012) a permis de montrer qu'une nouvelle méthode intégrant une correction de la gravité au *passive knee extension test* engendre l'application d'une force supérieure au segment jambier qu'avec la méthode classique (79.4 ± 7.6 N versus 68.7 ± 0.0 N, $P < 0.001$). La méthode intégrant la correction de la gravité permet d'obtenir un angle de genou supérieur (c.-à-d., une moindre flexion) que la méthode classique (73.1 ± 10.6° versus 68.8 ± 12.4°, $P < 0.001$). Cette méthode entraîne donc une évaluation plus précise de l'extensibilité puisqu'elle intègre le poids relatif du segment jambier dans la force appliquée pour étendre le genou du sujet. Cette considération est spécialement importante dans le monde du sport où des athlètes avec des morphologies diamétralement différentes sont testés (p. ex., lanceurs de poids versus demi-fondeurs). Cependant, cette méthode est plus contraignante que la méthode classique étant donné qu'elle nécessite deux mesures entrecoupées d'une étape de calcul.

2.1.2. Article 2 – Validity and reliability of maximal strength assessment of knee flexors and extensors using elastic bands

Ce travail (Guex, Daucourt, et al., 2014) a permis de valider une nouvelle méthode d'évaluation de la force maximale des ischio-jambiers et du quadriceps réalisée à l'aide de *Thera-Bands*®. La validité de la méthode proposée est très élevée ($r = 0.93$ pour les ischio-jambiers et le quadriceps) lorsqu'elle est comparée aux valeurs de force obtenues sur un appareil d'isocinétisme (considéré comme le *gold standard* en matière d'évaluation de la force) (Figure 16). Cette méthode est également hautement fiable (ICC = 0.98 et 0.99 ; CV = 3.44% et 2.33% ; SEM = 1.70 kg et 2.16 kg ; MDC = 4.73 kg et 5.99 kg pour, respectivement, les ischio-jambiers et le quadriceps). Cette étude montre donc que les *Thera-Bands*® représentent une alternative valide, fiable et peu couteuse à l'utilisation de matériel de fitness pour évaluer la force maximale des ischio-jambiers et du quadriceps. De plus, ils permettent de réaliser ces évaluations directement sur le terrain. Pour finir, cette étude suggère que les *Thera-Bands*® peuvent être utilisés pour réaliser des entraînements de force maximale (c.-à-d., avec des charges > 80% de la 1 RM).

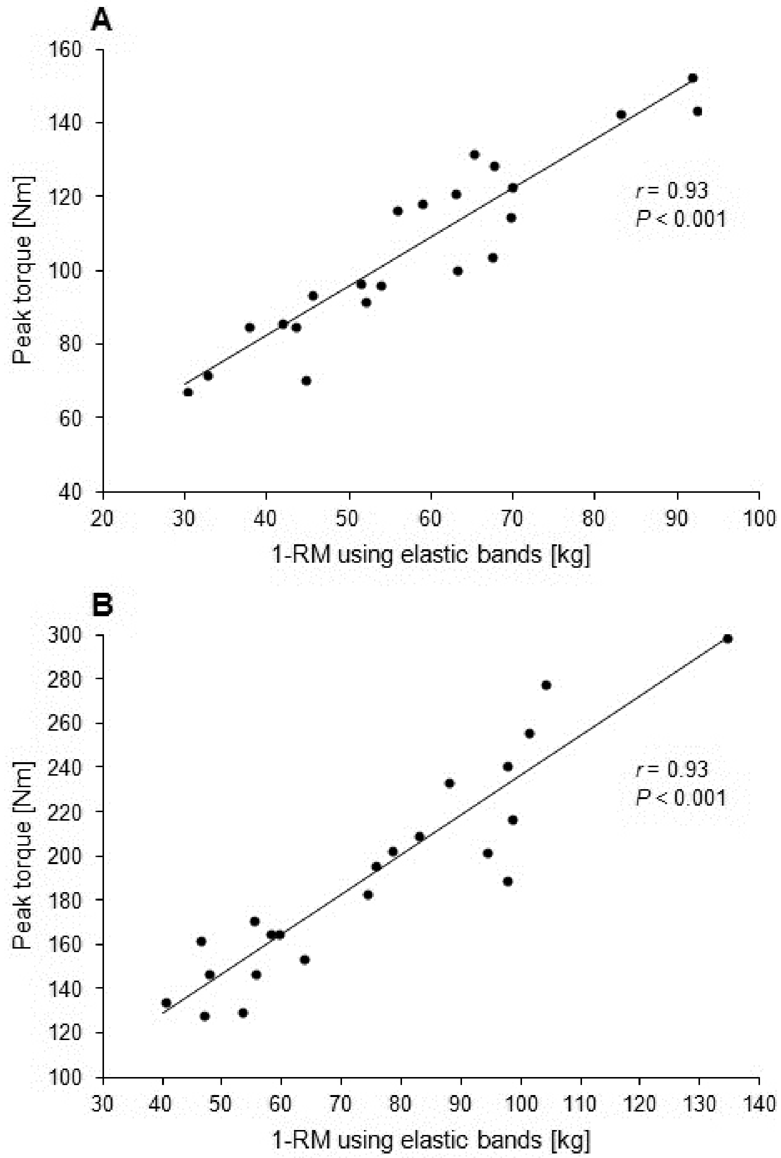


Figure 16. Corrélation entre les forces maximales obtenues à l'aide des *Thera-Bands*® et sur l'appareil d'isocinétisme pour A, les ischio-jambiers et B, le quadriceps.

2.2. Partie 2 – Fonction des ischio-jambiers à différentes longueurs musculaires

2.2.1. Article 3 – Influence of hip-flexion angle on hamstrings isokinetic activity in sprinters

Cette première étude (Guex, Gojanovic, et al., 2012) sur la fonction des ischio-jambiers à différentes longueurs musculaires a mis en évidence que la flexion de hanche influence directement la force des ischio-jambiers mais pas celle du quadriceps. En effet, sur un appareil d'isocinétisme, aucune différence de force du quadriceps n'a pu être observée entre 0°, 30°, 60° et 90° de flexion de hanche alors que, indifféremment du mode de contraction (c.-à-d., isométrique, en concentrique et en excentrique), les ischio-jambiers sont plus faibles à 0° qu'à tous les autres angles ($P < 0.001$) et plus forts à 90° qu'à 30° et 60° ($P < 0.05$). Ainsi, le ratio ischio-jambiers sur quadriceps est également directement influencé par la flexion de hanche. Finalement, aucune différence d'activité EMG des ischio-jambiers n'a pu être observée entre les différentes positions. Il est conclu que, en accord avec les notions sur la relation tension-longueur du muscle, l'augmentation de l'allongement des ischio-jambiers par un accroissement de la flexion de hanche entraîne une augmentation de leur force attribuable à la mise en tension des structures passives du muscle et à un meilleur recouvrement des ponts actines-myosines. En conséquence, l'évaluation de la force des ischio-jambiers des sprinteurs devrait être standardisée à 80° de flexion de hanche (c.-à-d., en position spécifique au sprint). De plus, l'efficacité des exercices de renforcement des ischio-jambiers pourrait être améliorée en contrôlant la flexion de hanche.

2.2.2. Article 4 – Effect of hip flexion angle on hamstring optimum length after a single set of concentric contractions

Cette étude (Guex, Degache, et al., 2013) a permis de démontrer qu'une série unique de 30 contractions concentriques des ischio-jambiers réalisée à 80° de flexion de hanche (c.-à-d., en position spécifique au sprint), soit sur la pente descendante de la relation tension-longueur (c.-à-d., au-delà de la longueur optimale) engendre un déplacement immédiat de l'angle optimal des ischio-jambiers d'environ 15° ($P < 0.01$) vers une position plus allongée (Figure 17, A). La même activité réalisée à 0° de flexion de hanche, soit sur la pente ascendante de la relation tension-longueur (c.-à-d., en-deçà de la longueur optimale) n'entraîne aucun déplacement de l'angle optimal (Figure 17, B). Conformément aux résultats de la première étude sur la fonction des ischio-jambiers à différentes longueurs musculaires, la force des ischio-jambiers est, pour chacune des 30 répétitions, supérieure à 80° versus 0° de flexion de hanche ($P < 0.01$). Enfin, il est à noter que les 30 contractions concentriques induisent le même niveau de fatigue quelle que soit la position. La réalisation d'une activité musculaire dans une position d'allongement permet donc, comme le mode de contraction excentrique, d'engendrer un déplacement immédiat de l'angle optimal vers une position plus allongée. Ce déplacement serait attribuable à une augmentation de la compliance en série du muscle, étape précoce des courbatures.

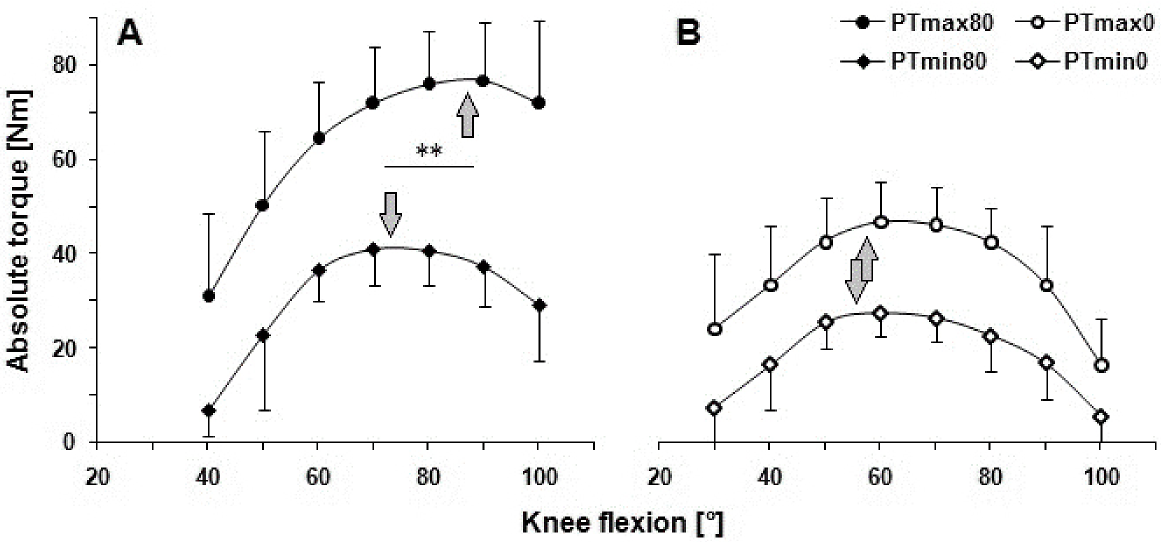


Figure 17. Relation tension-longueur au début et à la fin des 30 contractions concentriques à A, 80° et B, 0° de flexion de hanche. Les angles optimaux sont localisés par les flèches grises. ** $P < 0.01$, pour la différence entre l'angle optimal au début et à la fin des 30 contractions.

2.3. Partie 3 – Applications dans la pratique

2.3.1. Article 5 – Conceptual framework for strengthening exercises to prevent hamstring strains

Cette revue de la littérature (Guex & Millet, 2013) a permis de proposer des modalités précises de renforcement des ischio-jambiers destinées aux sprinteurs dans une perspective de prévention des blessures (Tableau 1). Pour répondre aux exigences mécaniques de la fin de phase d'oscillation du sprint, il est proposé de réaliser des exercices de renforcement excentrique en chaîne cinétique ouverte avec des charges lourdes (c.-à-d., à ≥ 100% de la 1 RM) à des vitesses angulaires lentes ou modérées. Sur la base des résultats obtenus dans la partie sur la fonction des ischio-jambiers à différentes longueurs musculaires, il est proposé de préférer des exercices réalisés à un niveau d'allongement musculo-tendineux important. (c.-à-d., au-delà de la longueur optimale). Ceci afin de favoriser un déplacement de l'angle optimal vers une position plus allongée et permettre ainsi de limiter le risque d'*overstretch* des ischio-jambiers lors de la fin de phase d'oscillation du sprint.

Tableau 1. Proposition d'un nouveau cadre théorique pour la prévention des blessures des ischio-jambiers chez le sprinteur.

Paramètres	Position de départ	Amplitude	Position d'arrivée
Type de contraction	Excentrique		
Charge (%)	≥ 100% de la 1 RM		
Amplitude			
Flexion de hanche (°)	80	0	80
Flexion de genou (°)	130	110	20
Indice d'allongement	-50		+60
Vitesse angulaire	Lente à modérée		
Exercices uni-/bilatéraux	Unilatéraux		
Chaine cinétique	Ouverte		

RM, répétition maximale.

2.3.2. Article 6 – Influence of a 6-weeks eccentric training on hamstring functional parameters and injury incidence in sprinters during a winter season

Ce travail (Guex, Lugrin, et al., 2014) a permis de montrer qu'un programme de renforcement excentrique des ischio-jambiers (réalisé en chaîne ouverte, avec des charges lourdes et construit pour couvrir toute la relation tension-longueur du muscle) durant les six premières semaines d'entraînement de la préparation hivernale de sprinteurs entraîne une augmentation significative de la force et de la flexibilité. La force est améliorée de 15% ($P < 0.001$) en concentrique à 60°/s, de 18% ($P = 0.004$) en excentrique à 30°/s et de 20% ($P < 0.001$) en excentrique à 120°/s. Les ratios conventionnels ($P = 0.002$) et fonctionnels ($P = 0.002$) sont tous les deux augmentés de 11%. Enfin, la flexibilité est améliorée de 4° ($P = 0.031$). Malgré l'intensité importante du renforcement excentrique (80 à 110% de la 1 RM) aucun athlète ne s'est blessé pendant l'intervention. Durant les trois mois de suivi post-intervention, trois athlètes du groupe contrôle (incidence de 30% et de 1.99 par 1000 h de pratique ; blessure survenue après 92.0 ± 27.2 h d'exposition et résultant en 23.3 ± 16.1 jours d'indisponibilité en moyenne) et deux du groupe intervention (incidence de 20% et de 1.28 par 1000 h de pratique ; blessure survenue après 140.3 ± 5.3 h d'exposition et résultant en 14.5 ± 0.7 jours d'indisponibilité en moyenne) se sont blessés. Les résultats du dernier test avant la blessure montrent que les ischio-jambiers du membre inférieur atteint sont en moyenne 13% plus faible ($P = 0.013$) en concentrique à 60°/s et 7% plus faible ($P = 0.037$) en excentrique à 30°/s, avec un ratio conventionnel diminué de 13% ($P < 0.001$) et un angle optimal augmenté (c.-à-d., une longueur musculaire optimale diminuée) de 11° ($P = 0.025$). En conclusion, une intervention excentrique spécifique régulière durant toute la saison pourrait être un moyen pertinent de diminuer l'incidence des blessures des ischio-jambiers chez les sprinteurs en améliorant un certain nombre de facteurs de risque potentiels comme la force, les ratios conventionnels et fonctionnels et la flexibilité.

Chapitre 3. Discussion & perspectives

3.1. Discussion des résultats

Selon sa sévérité, la déchirure des ischio-jambiers peut contraindre le sportif à une période d'arrêt relativement prolongée. Dans le cas d'athlètes professionnels, un arrêt forcé représente un coût direct pour le club qui l'emploie (Woods et al., 2002). En plus de cela, lors du retour au sport, la performance du sportif ayant subi une lésion des ischio-jambiers est significativement réduite (Mendiguchia et al., 2014; Verrall et al., 2006) et le risque de nouvelle blessure est augmenté de près de 12 fois (Hagglund et al., 2006). Dès lors, une prise en charge préventive s'impose. Dans ce domaine, des exercices de renforcement basés sur le mode de contraction excentrique comme le *Nordic hamstring* se sont montrés efficaces pour réduire le risque de blessure (Arnason et al., 2008; Brooks et al., 2006; Gabbe et al., 2006; Petersen et al., 2011). Cependant, au vu des fortes contraintes que subissent les ischio-jambiers lors de la course à haute vitesse, il était nécessaire de pousser la réflexion concernant le choix et les modalités des exercices de renforcement afin d'améliorer leur spécificité.

Avant de se pencher sur ces modalités, deux premiers travaux se sont intéressés à des outils d'évaluation de terrain des ischio-jambiers. Les sportifs n'ont pas systématiquement accès à des outils d'évaluation de laboratoire, il est donc important d'avoir des outils de terrain valides et fiables. Dans cette optique, l'Article 1 propose une optimisation du *passive knee extension test* qui est un test fréquemment utilisé pour évaluer la souplesse des ischio-jambiers (Guex, Fourchet, et al., 2012). La modification présentée a l'avantage d'être plus adaptée aux différents gabarits des athlètes puisqu'elle prend en compte le poids relatif de leur segment jambier. Cependant, elle est plus complexe à réaliser puisqu'elle nécessite de prendre deux mesures entrecoupées d'une étape de calcul. L'Article 2, présente une nouvelle manière d'évaluer la force des ischio-jambiers et du quadriceps sans appareil de fitness (Guex, Daucourt, et al., 2014). La méthode proposée s'est montrée tout aussi valide et fiable qu'une évaluation directe de la force des ischio-jambiers et du quadriceps réalisée sur des appareils de fitness (Levinger et al., 2009). La forte plus-value de cette étude réside dans le fait qu'elle démontre que les *Thera-Bands®* peuvent être utilisés pour l'entraînement de la force puisqu'une charge peut être choisie de manière précise (en pourcentage de la 1 RM) en sélectionnant la couleur, le nombre de couches et la longueur terminale du *Thera-Band®* lors de l'exercice. Avec un nombre approprié de répétitions et de séries (ACSM, 2009), il est ainsi possible d'entraîner la force maximale, l'hypertrophie, la puissance ou la force endurance d'un groupe musculaire directement sur le terrain.

Concernant les modalités de renforcement dans une perspective de prévention des déchirures des ischio-jambiers, cette thèse s'est principalement intéressée à la question du niveau d'allongement musculo-tendineux. Le but était d'observer l'activité des ischio-jambiers lorsqu'ils sont placés dans des positions spécifiques au sprint (c.-à-d., entre 60° et 90°) ou non (c.-à-d., entre 0° et 30°). Les résultats obtenus dans les Articles 3 & 4 montrent que les ischio-jambiers développent une force supérieure s'ils sont placés, par le biais d'une flexion de hanche importante, dans une position spécifique au sprint (Guex, Degache, et al., 2013; Guex, Gojanovic, et al., 2012). En effet, quel que soit le mode de contraction, la force produite à 90° de flexion de hanche par les fléchisseurs du genou est plus de 50% supérieure à celle produite à 0° de flexion de hanche (Guex, Gojanovic, et al., 2012). Ceci est en accord avec les autres études ayant investigué l'influence de la flexion de hanche sur la fonction des ischio-jambiers (Bohannon et al., 1986; Lunnen et al., 1981; Mohamed et al., 2002; Worrell et al., 1989). Due à la nature bi-articulaire des ischio-jambiers, lorsque la hanche est fléchie de manière importante, les structures passives du complexe musculo-tendineux sont mises en tension et assistent ainsi les composantes contractiles dans leur production de force au niveau de l'articulation du genou. Cette situation d'allongement est donc favorable à la production de force. Cependant, elle augmente également le risque de lésion musculaire. En effet, il a été montré que le niveau d'étirement d'un muscle est le facteur déterminant dans la survenue des lésions musculaires (Garrett, 1990; Garrett et al., 1987; Mair et al., 1996).

Dans l'Article 4, suite à 30 répétitions concentriques réalisées dans une position spécifique au sprint (c.-à-d., à 80° de flexion de hanche), un déplacement de 15° de l'angle optimal des ischio-jambiers vers une position plus allongée est trouvé (Guex, Degache, et al., 2013). Lorsque la même activité est réalisée dans une position courte comparable à celle du *Nordic hamstring* (c.-à-d., à 0° de flexion de hanche), aucune modification de l'angle optimal n'est observée. A la suite d'une activité excentrique, une modification de l'angle optimal est proposée comme un indicateur fiable des dégâts musculaires engendrés par cette activité (Morgan, 1990). Dans l'Article 4, le fait d'avoir observé ce déplacement suite à une activité concentrique (qui n'est pas connue pour engendrer des microlésions musculaires) réalisée dans une position longue suggère que le niveau d'allongement est un stimulus au moins aussi important que le mode de contraction excentrique pour générer des microlésions au niveau musculaire. Ce résultat confirme que lorsque les ischio-jambiers sont activés alors que la hanche est en position de flexion (comme c'est le cas lors de la fin de phase d'oscillation du sprint), ils sont plus susceptibles de subir des dommages musculaires.

Le déplacement de l'angle optimal vers une position plus longue est proposé comme un moyen de diminuer le risque de déchirure des ischio-jambiers (Brockett et al., 2004; Proske et al., 2004). Une telle adaptation a été retrouvée dans plusieurs études à la suite de programmes de renforcement excentrique des ischio-jambiers (Brockett et al., 2001; Brughelli, Mendiguchia, et al., 2010; Clark et al., 2005; Kilgallon et al., 2007; Potier et al., 2009). Cette adaptation est attribuable à une augmentation de la longueur des faisceaux musculaires (Blazevich et al., 2007; Potier et al., 2009; Seynnes et al., 2007). Il est intéressant de constater qu'un entraînement réalisé à un niveau d'allongement important, mais selon un mode de contraction concentrique permet d'obtenir des adaptions comparables en termes d'allongement des fibres musculaires (Blazevich et al., 2007). Cela suggère, au même titre que les résultats de l'Article 3, que le mode de contraction musculaire n'est pas le seul stimulus permettant une adaptation de l'architecture musculaire. Le niveau d'allongement lors du renforcement semble au moins aussi déterminant.

Cette notion est centrale dans cette thèse et a donc été reprise dans l'Article 5 (Guex & Millet, 2013). Ce dernier propose une trame pour choisir les modalités de renforcement des ischio-jambiers dans une perspective de prévention des blessures. Bien sûr, le mode de contraction excentrique est à prioriser mais, suite aux résultats obtenus dans les Articles 3 & 4, il est proposé de préférer des exercices réalisés dans une position spécifique au sprint (c.-à-d., à un niveau d'allongement important des ischio-jambiers) afin d'accentuer les adaptations de l'architecture musculaire (c.-à-d., un allongement des faisceaux musculaires sans augmentation de l'angle de pennation). D'autres auteurs partagent cette proposition (Brughelli et al., 2008; DeWitt et al., 2014; Malliaropoulos et al., 2012; Opar et al., 2012; Schache et al., 2012; Schmitt et al., 2012). Toutefois, les travaux réalisés dans le cadre de cette thèse sont les premiers à justifier de manière objective ce besoin (Guex, Degache, et al., 2013; Guex, Gojanovic, et al., 2012).

Le muscle a une capacité remarquable d'adaptation aux stimuli mécaniques (Wisdom et al., 2014). Ainsi, il a été montré que l'architecture des ischio-jambiers de joueurs de football australien est très différente de celle de cyclistes (Brughelli, Cronin, et al., 2010). En effet, les footballeurs australiens ont un angle optimal plus faible, des faisceaux musculaires plus longs, et un angle de pennation plus faible que les cyclistes. Selon les auteurs de cet article, ces différences seraient attribuables aux adaptations à long terme liées à l'entraînement spécifique de chaque sport. Cette idée est renforcée par une étude qui a montré que des femmes portant régulièrement des talons hauts ont des gastrocnémiens composés de faisceaux musculaires plus courts que des femmes n'en portant jamais (Csapo et al., 2010). Ces deux exemples montrent que le muscle est capable de s'adapter de manière ciblée aux contraintes qui lui sont imposées. Dès lors, il apparaît primordial d'intégrer des exercices spécifiques dans la préparation des sprinteurs, c.-à-d. des exercices réalisés à un niveau d'allongement musculo-tendineux important. Ceci pourrait laisser penser que des exercices d'étirement musculaire seraient suffisants pour obtenir les adaptations architecturales recherchées. Cependant, il a été montré que la synthèse protéique musculaire augmente de façon bien plus importante lorsqu'un muscle étiré est stimulé (Goldspink, 1978;

Goldspink, 1999). Ainsi, des renforcements réalisés en position longue entraîneront une augmentation plus importante du nombre de sarcomères en série que des exercices d'étirement (Seynnes et al., 2007).

Afin de quantifier de manière simple le niveau d'allongement des ischio-jambiers lors des exercices, il est proposé dans l'Article 5 de soustraire l'angle de flexion de genou à l'angle de hanche (Guex & Millet, 2013). Si le résultat est positif, les ischio-jambiers sont allongés au-delà de leur longueur optimale. S'il est négatif, ils sont alors en position plus courte. Cette méthode donne des résultats en accord avec les observations faites sur la longueur des faisceaux musculaires du biceps fémoral à différents angles de genou et de hanche (Chleboun et al., 2001). Afin de permettre de limiter le risque d'*overstretch* des ischio-jambiers lors de la fin de phase d'oscillation du sprint, il est proposé de se focaliser sur des exercices incluant une flexion de hanche de 80° permettant ainsi d'atteindre des niveaux d'allongement au moins aussi élevés que ceux retrouvés lors du sprint (Figure 18).

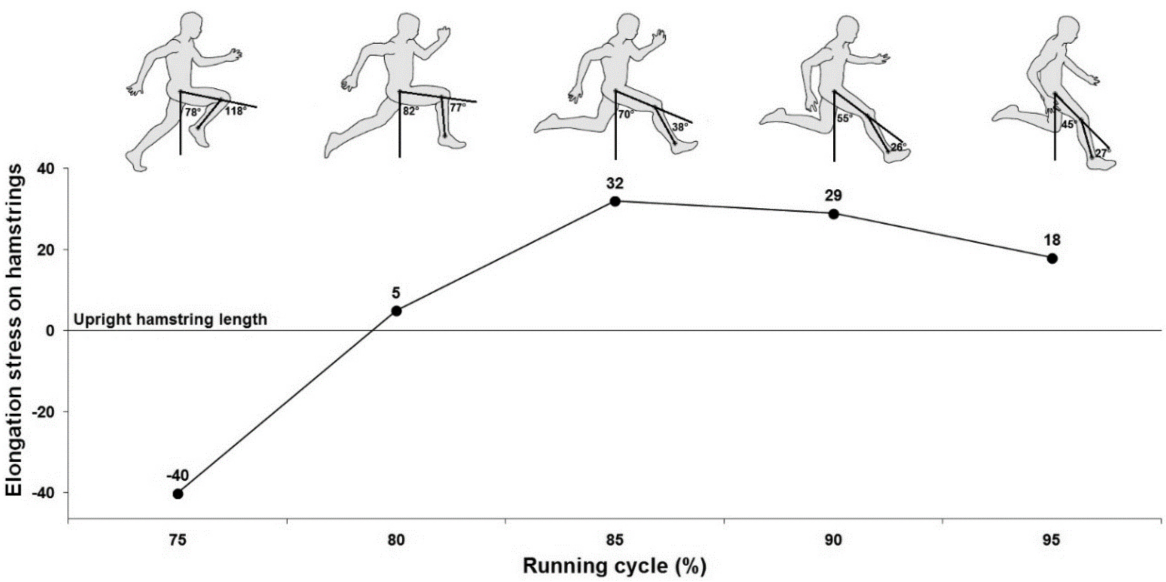


Figure 18. Niveaux d'allongement des ischio-jambiers lors de la phase d'oscillation du sprint. Le niveau d'allongement est obtenu en soustrayant l'angle de genou à celui de la hanche (Guex & Millet, 2013).

Dans le but d'étudier l'impact des recommandations de l'Article 5, un programme de renforcement excentrique composé de deux exercices, réalisé deux fois par semaine durant six semaines a été conçu (Article 6). L'idée était de travailler les ischio-jambiers au niveau de leurs deux articulations (c.-à-d., la hanche et le genou) et de couvrir l'ensemble de la courbe tension-longueur (c.-à-d., un exercice réalisé en position courte et un en position longue). Ainsi, il a été choisi d'utiliser le *lying hamstring curl*, renommé pour cette étude *eccentric knee extension* (EKE) (Figure 19, A) et un exercice inventé, nommé *eccentric hip extension* (EHE) (Figure 19, B). Ce programme s'est montré efficace pour améliorer plusieurs facteurs de risque comme la force (+15% en concentrique, +18 à 20% en excentrique) des ischio-jambiers, les ratios ischio-jambiers sur quadriceps conventionnels (+11%) et fonctionnels (+11%) ainsi que la flexibilité (+4°). Ces améliorations sont comparables à celles obtenues dans d'autres études sur les effets de différentes interventions excentriques (Askling et al., 2003; Iga et al., 2012; Kaminski et al., 1998; Mjolsnes et al., 2004; Nelson et al., 2004; Potier et al., 2009). Concernant l'angle optimal, comme dans l'étude de Iga et al. (2012) sur le *Nordic hamstring*, en raison d'une grande variabilité dans les résultats, seul un déplacement non-significatif de 4° vers une position plus allongée a pu être retrouvé. A la suite de cette intervention, le faible nombre de sujets inclus dans l'étude n'a pas permis de vérifier si les membres du groupe excentrique ont plus été sujets aux blessures que ceux du groupe contrôle. Cependant, en accord avec des études précédentes (Croisier et al., 2008; Orchard et al., 1997; Sugiura et al., 2008; Yeung et al., 2009), il a été trouvé, chez les athlètes blessés, une force et un ratio inférieurs du côté qui allait se blesser par la suite. De plus, et cette étude est la première à le montrer, un angle optimal augmenté de 11° (c.-à-d., une longueur musculaire optimale diminuée) a été retrouvé au niveau des futurs ischio-jambiers blessés. Ceci a pour conséquence d'entraîner une activité des ischio-jambiers à des niveaux d'allongement plus importants lors du sprint et donc d'augmenter le risque de lésion musculaire.

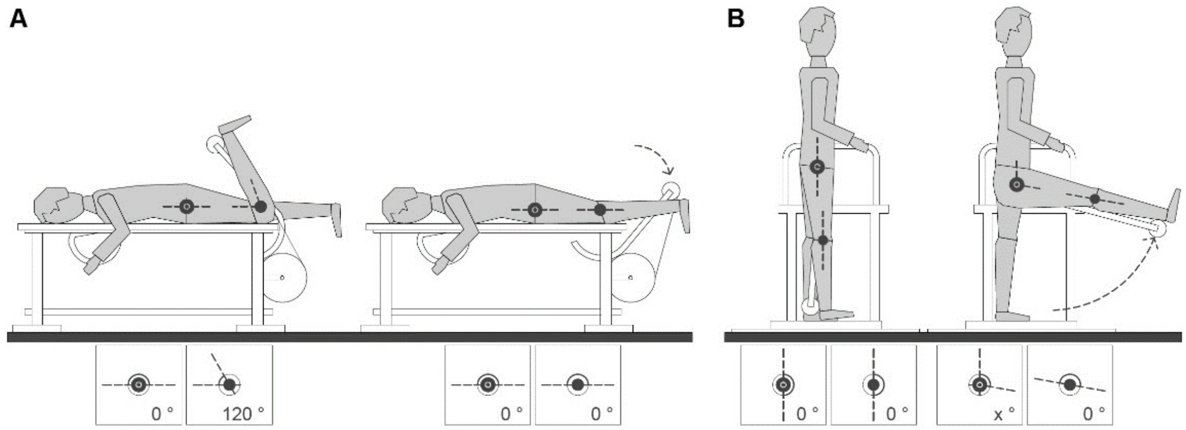


Figure 19. A, *eccentric knee extension* et B, *eccentric hip flexion* (Guex, Lugrin, et al., 2014).

Le programme de renforcement proposé dans l'Article 6 n'est pas parfait. En effet, l'accent aurait d'avantage dû être mis sur des exercices réalisés à une longueur musculaire importante. De plus, ce type d'intervention devrait être maintenu durant toute la saison, avec un volume important lors de la phase de préparation (c.-à-d., deux à trois séances hebdomadaires) et une séance hebdomadaire de maintien en phase de compétition. Quoiqu'il en soit, l'Article 6 montre que, directement au début de la phase de préparation, l'intensité (c.-à-d., la charge) peut être élevée (c.-à-d., > 80% de la 1 RM) sans risque de blessure. En plus du niveau d'allongement des ischio-jambiers et du mode de contraction excentrique, l'utilisation de charges élevées est le troisième paramètre clé pour la prévention des déchirures des ischio-jambiers dès lors qu'il a été montré qu'un muscle fort est mieux protégé contre les lésions musculaires (Garrett et al., 1987). Le recours à des charges élevées est d'autant plus important que les contraintes engendrées par le sprint imposent aux ischio-jambiers des contractions supra-maximales 1.5 fois (lors de la fin de phase d'oscillation) et 1.4 fois (lors de la fin de phase d'appui) supérieures à leur force maximale isométrique (Sun et al., 2014).

Finalement, cette thèse a ouvert de nouvelles perspectives en lien avec la prévention des blessures des ischio-jambiers. Ces dernières sont présentées dans la partie suivante.

3.2. Perspectives

La réalisation de cette thèse a tout d'abord permis de proposer une série d'exercices de renforcement de terrain simples et spécifiques au sprint. Ensuite, elle a permis d'initier une réflexion sur le développement d'un appareil de renforcement spécifique aux contraintes de la course à haute vitesse. Enfin, elle a ouvert la porte à de nouveaux projets de recherche sur cette thématique.

3.2.1. Exercices spécifiques avec Thera-Bands®

Trois exercices spécifiques au sprint sont présentés ci-dessous. Ils peuvent tous être réalisés à l'aide d'un système à poulie en salle de fitness. Ils peuvent également être directement réalisés sur le terrain à l'aide de *Thera-Bands®* du fait de la possibilité de travailler la force maximale avec ce type de bandes élastiques (Guex, Daucourt, et al., 2014).

Sprinter hamstring curl

Cet exercice est spécifique à la fin de phase d'oscillation du sprint. Comme lors de cette dernière, l'objectif est de freiner l'extension du genou. Le retour à la position de départ (phase concentrique) peut être facilité par une autre personne. L'exercice peut être réalisé en position debout (Figure 20, A) ou en décubitus dorsal (Figure 20, B). L'indice d'allongement des ischio-jambiers est négatif en position de départ (90 - 130 = -40) et positif en position d'arrivée (90 - 10 = 80). En comparaison, lors du *Nordic hamstring*, l'indice d'allongement n'est jamais positif (de -90 à 0).

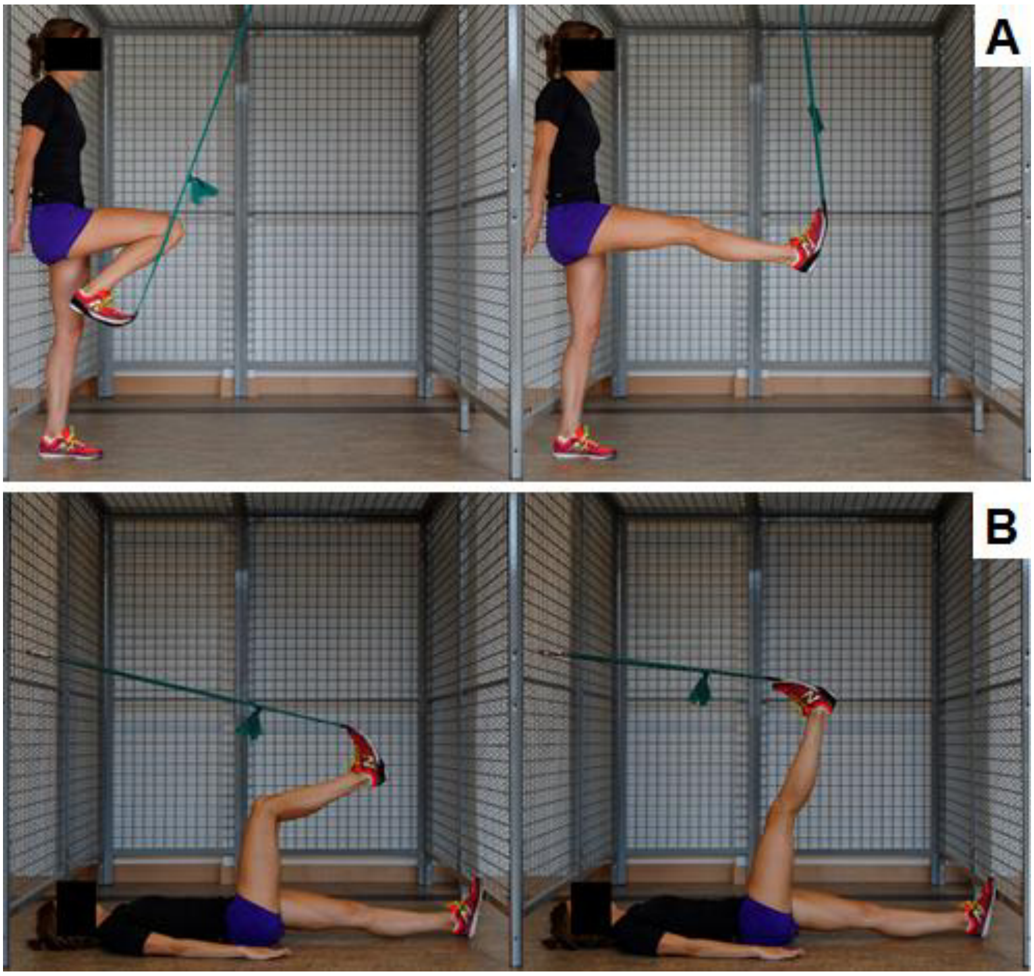


Figure 20. *Sprinter hamstring curl* réalisé A, debout ou B, en décubitus dorsal.

Eccentric hip flexion

Cet exercice est celui utilisé dans l'Article 6. Les ischio-jambiers sont activés pour freiner la flexion de la hanche. L'indice d'allongement est nul en position de départ (0 - 0 = 0) et positif en position d'arrivée (90 - 0 = 90). Le retour à la position de départ (phase concentrique) peut être facilité par une autre personne. L'exercice peut être réalisé en position debout (Figure 21, A) ou en décubitus dorsal (Figure 21, B).

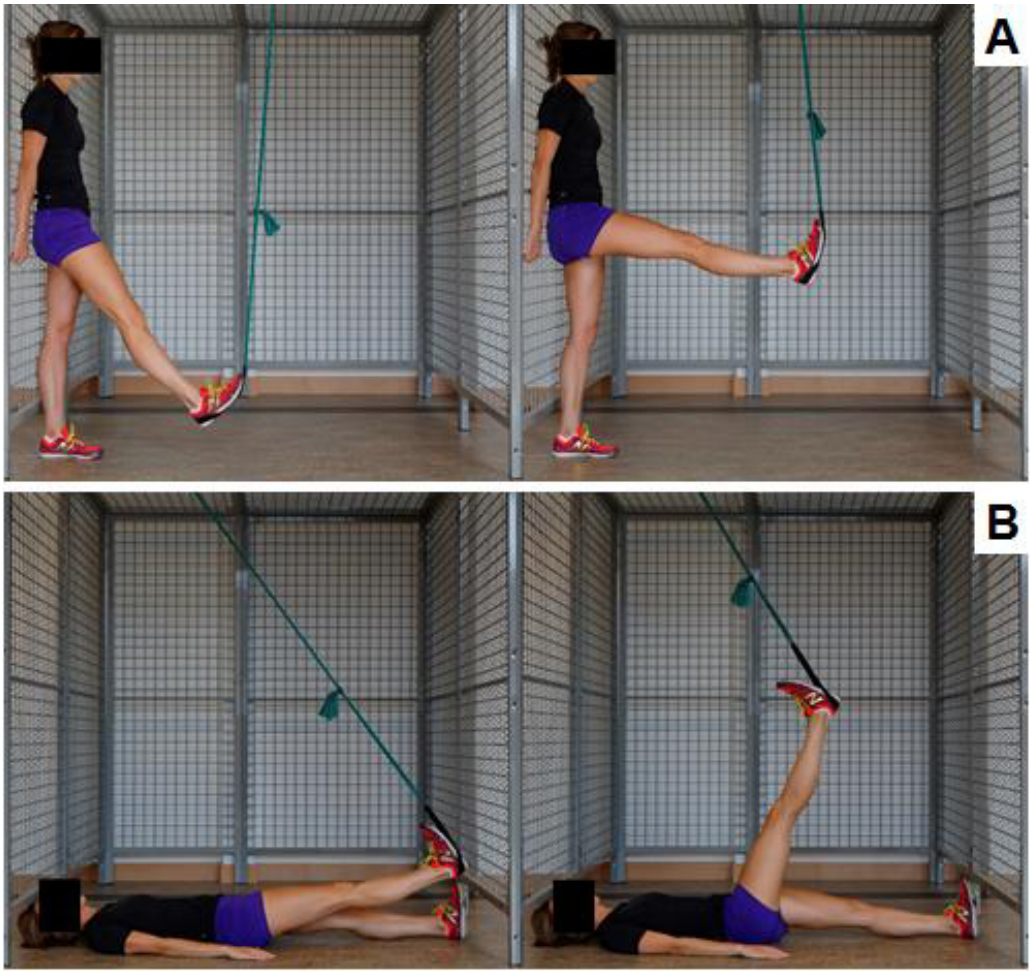


Figure 21. *Eccentric hip flexion* réalisé A, debout ou B, en décubitus dorsal.

Single leg deadlift

Cet exercice présenté en introduction (cf., 1.5.1. Principaux exercices de renforcement des ischio-jambiers) peut être adapté en utilisant un *Thera-band*® dans le but d'augmenter la charge (Figure 22). L'indice d'allongement est nul en position de départ (0 - 0 = 0) et, comme pour les autres exercices proposés, positif en position d'arrivée (90 - 0 = 90).

Figure 22. *Single leg deadlift* avec *Thera-Band®*.

3.2.2. Développement d'un appareil spécifique

Sur la base des recommandations réalisées dans l'Article 5 et en collaboration avec la Haute Ecole d'Ingénierie et de Gestion du Canton de Vaud (HEIG-VD), un projet de développement d'un appareil de renforcement des ischio-jambiers a été initié. Il vise à développer un système motorisé spécifique au sprint permettant le renforcement et l'évaluation de la force des ischio-jambiers. Dans un premier temps, un étudiant a effectué son travail de Bachelor sur ce dispositif. Il a proposé des plans (Figure 23) pour la fabrication d'un appareil permettant de réaliser des flexions du genou en concentrique ou en excentrique de manière isocinétique à différentes vitesses. Sur l'appareil, le sujet est dans la même position que lors de l'exercice du *sprinter hamsting curl* (cf., 3.2.1. Exercices spécifiques avec *Thera-Bands®*). Tout comme un appareil d'isocinétisme, le système est également conçu pour évaluer la force puisqu'il est muni de capteurs de force. Par la suite, il est prévu qu'un étudiant travaille encore sur le développement de l'appareil dans le cadre de son Master. Ensuite, une demande de fonds pour un projet CTI (Commission pour la Technologie et l'Innovation) pourrait être envisagée afin de fabriquer un prototype.

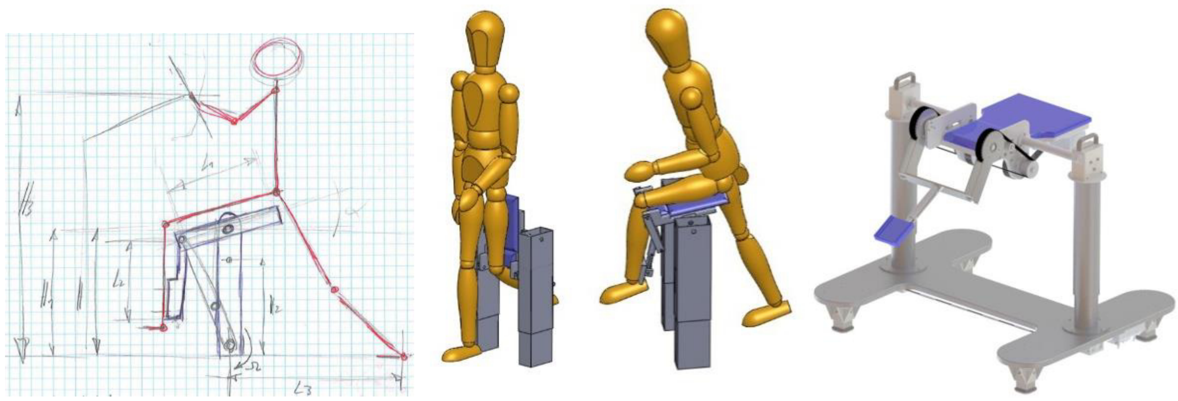


Figure 23. Différentes étapes du développement d'un système motorisé spécifique au sprint permettant le renforcement et l'évaluation de la force des ischio-jambiers.

3.2.3. Projets de recherche

Pour finir, cette thèse a ouvert la voie à de futurs projets de recherche. Tout d'abord, un travail visant à comparer les adaptations à un entraînement de force excentrique réalisé en position courte versus longue est actuellement en cours dans le cadre d'un travail de Master d'une étudiante en sciences du sport à l'Institut des Sciences du Sport de l'Université de Lausanne (ISSUL). Une revue de littérature sur les effets d'un entraînement pliométrique versus excentrique sur le complexe musculo-tendineux est également en cours dans le cadre d'un travail de Bachelor de deux étudiants en physiothérapie à la Haute Ecole de Santé Vaud (HESAV). Enfin, en collaboration avec le département de l'appareil locomoteur du Centre Hospitalier Universitaire Vaudois (CHUV), il est envisagé de comparer prochainement l'évolution de la force à la suite d'un programme d'entraînement réalisé à l'aide de *Thera-bands*® versus sur un appareil de fitness.

3.3. Conclusion

En plus de proposer de nouveaux outils d'évaluation des ischio-jambiers, cette thèse met en avant l'importance de la spécificité des exercices par rapport au sprint dans la prévention des blessures des sportifs à risque (Figure 24). La littérature actuelle a largement démontré l'importance de prescrire des exercices de renforcement excentrique. Les résultats des différents travaux réalisés dans le cadre de cette thèse, viennent compléter cette prescription en démontrant l'importance de réaliser ces exercices à des niveaux d'allongement musculo-tendineux importants ce qui peut facilement être réalisé par l'intermédiaire d'une position de flexion de hanche.

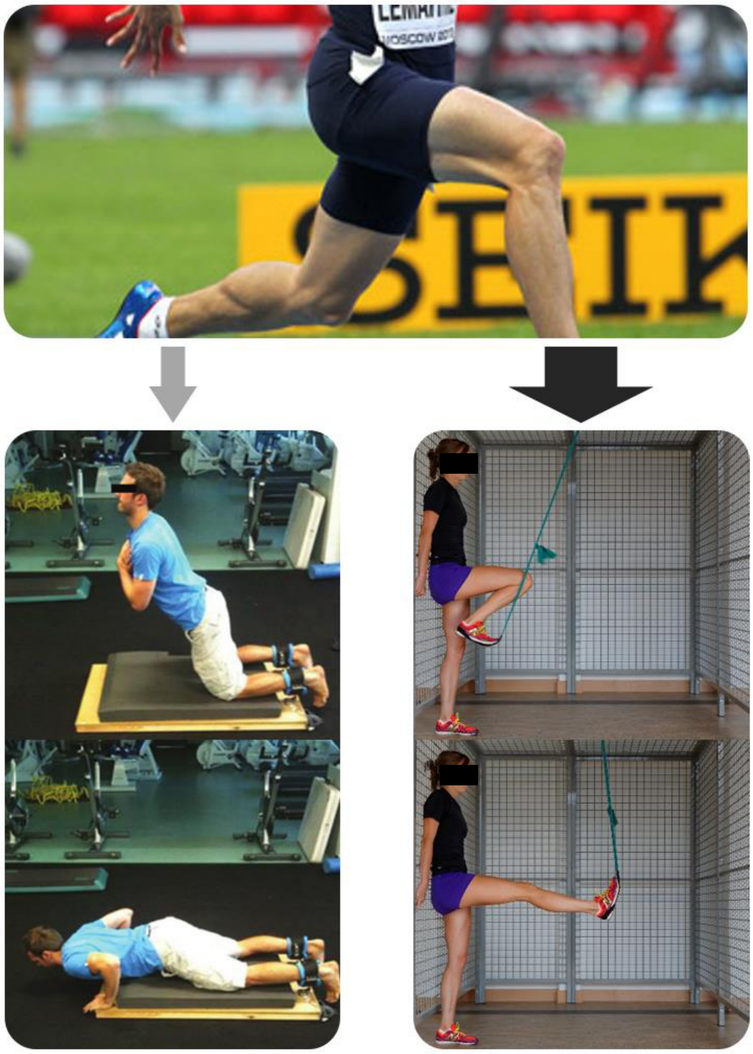


Figure 24. Le choix d'un exercice dans une perspective de prévention des blessures des ischio-jambiers doit se baser sur sa spécificité en regard des contraintes imposées par le sprint (www.runblogrun.com). Un exercice comme le *sprinter hamstring curl* devrait dès lors être préféré au *Nordic hamstring* (Opar et al., 2013).

Chapitre 4. Bibliographie

4.1. Liste des références

ACSM. (2009). American College of Sports Medicine position stand. Progression models in resistance training for healthy adults. *Medicine and Science in Sports and Exercise, 41*(3), 687-708.

Agre, J. C. (1985). Hamstring injuries. Proposed aetiological factors, prevention, and treatment. *Sports medicine, 2*(1), 21-33.

Alonso, J. M., Edouard, P., Fischetto, G., Adams, B., Depiesse, F., & Mountjoy, M. (2012). Determination of future prevention strategies in elite track and field: analysis of Daegu 2011 IAAF Championships injuries and illnesses surveillance. *British Journal of Sports Medicine, 46*(7), 505-514.

Arnason, A., Andersen, T. E., Holme, I., Engebretsen, L., & Bahr, R. (2008). Prevention of hamstring strains in elite soccer: an intervention study. *Scandinavian journal of medicine & science in sports, 18*(1), 40-48.

Askling, C., Karlsson, J., & Thorstensson, A. (2003). Hamstring injury occurrence in elite soccer players after preseason strength training with eccentric overload. *Scandinavian journal of medicine & science in sports, 13*(4), 244-250.

Askling, C. M., Malliaropoulos, N., & Karlsson, J. (2012). High-speed running type or stretching-type of hamstring injuries makes a difference to treatment and prognosis. *British Journal of Sports Medicine, 46*(2), 86-87.

Askling, C. M., Tengvar, M., Saartok, T., & Thorstensson, A. (2007a). Acute first-time hamstring strains during high-speed running: a longitudinal study including clinical and magnetic resonance imaging findings. *The American journal of sports medicine, 35*(2), 197-206.

Askling, C. M., Tengvar, M., Saartok, T., & Thorstensson, A. (2007b). Acute first-time hamstring strains during slow-speed stretching: clinical, magnetic resonance imaging, and recovery characteristics. *The American journal of sports medicine, 35*(10), 1716-1724.

Blazevich, A. J., Cannavan, D., Coleman, D. R., & Horne, S. (2007). Influence of concentric and eccentric resistance training on architectural adaptation in human quadriceps muscles. *J Appl Physiol (1985), 103*(5), 1565-1575.

Bohannon, R. W., Gajdosik, R. L., & LeVeau, B. F. (1986). Isokinetic knee flexion and extension torque in the upright sitting and semireclined sitting positions. *Physical Therapy, 66*(7), 1083-1086.

Bradley, P. S., & Portas, M. D. (2007). The relationship between preseason range of motion and muscle strain injury in elite soccer players. *Journal of strength and conditioning research / National Strength & Conditioning Association, 21*(4), 1155-1159.

Brockett, C. L., Morgan, D. L., & Proske, U. (2001). Human hamstring muscles adapt to eccentric exercise by changing optimum length. *Medicine and Science in Sports and Exercise, 33*(5), 783-790.

Brockett, C. L., Morgan, D. L., & Proske, U. (2004). Predicting hamstring strain injury in elite athletes. *Medicine and Science in Sports and Exercise, 36*(3), 379-387.

Brooks, J. H., Fuller, C. W., Kemp, S. P., & Reddin, D. B. (2005). Epidemiology of injuries in English professional rugby union: part 1 match injuries. *British Journal of Sports Medicine, 39*(10), 757-766.

Brooks, J. H., Fuller, C. W., Kemp, S. P., & Reddin, D. B. (2006). Incidence, risk, and prevention of hamstring muscle injuries in professional rugby union. *The American journal of sports medicine, 34*(8), 1297-1306.

Brughelli, M., & Cronin, J. (2008). Preventing hamstring injuries in sport. *Strength and Conditioning Journal, 30*(1), 55-64.

Brughelli, M., Cronin, J., & Nosaka, K. (2010). Muscle architecture and optimum angle of the knee flexors and extensors: a comparison between cyclists and Australian Rules football players. *Journal of strength and conditioning research / National Strength & Conditioning Association, 24*(3), 717-721.

Brughelli, M., Mendiguchia, J., Nosaka, K., Idoate, F., Arcos, A. L., & Cronin, J. (2010). Effects of eccentric exercise on optimum length of the knee flexors and extensors during the preseason in professional soccer players. *Physical therapy in sport : official journal of the Association of Chartered Physiotherapists in Sports Medicine, 11*(2), 50-55.

Burkett, L. N. (1970). Causative factors in hamstring strains. *Medicine and science in sports, 2*(1), 39-42.

Chleboun, G. S., France, A. R., Crill, M. T., Braddock, H. K., & Howell, J. N. (2001). In vivo measurement of fascicle length and pennation angle of the human biceps femoris muscle. *Cells, tissues, organs, 169*(4), 401-409.

Chumanov, E. S., Heiderscheit, B. C., & Thelen, D. G. (2007). The effect of speed and influence of individual muscles on hamstring mechanics during the swing phase of sprinting. *Journal of biomechanics, 40*(16), 3555-3562.

Chumanov, E. S., Schache, A. G., Heiderscheit, B. C., & Thelen, D. G. (2012). Hamstrings are most susceptible to injury during the late swing phase of sprinting. *British Journal of Sports Medicine, 46*(2), 90.

Clark, R., Bryant, A., Culgan, J. P., & Hartley, B. (2005). The effects of eccentric hamstring strength training on dynamic jumping performance and isokinetic strength parameters: a pilot study on the implications for the prevention of hamstring injuries. *Phys Ther Sport, 6*(2), 67-73.

Clark, R. A. (2008). Hamstring injuries: risk assessment and injury prevention. *Annals of the Academy of Medicine, Singapore, 37*(4), 341-346.

Croisier, J. L., Ganteaume, S., Binet, J., Genty, M., & Ferret, J. M. (2008). Strength imbalances and prevention of hamstring injury in professional soccer players: a prospective study. *The American journal of sports medicine, 36*(8), 1469-1475.

Csapo, R., Maganaris, C. N., Seynnes, O. R., & Narici, M. V. (2010). On muscle, tendon and high heels. *The Journal of experimental biology, 213*(Pt 15), 2582-2588.

Dahmane, R., Djordjevic, S., & Smerdu, V. (2006). Adaptive potential of human biceps femoris muscle demonstrated by histochemical, immunohistochemical and mechanomyographical methods. *Med Biol Eng Comput, 44*(11), 999-1006.

Danowski, R.-G., & Chanussot, J.-C. (2005). *Traumatologie du sport* (7th ed.). Paris: Masson.

DeWitt, J., & Vidale, T. (2014). Recurrent hamstring injury: consideration following operative and non-operative management. *Int J Sports Phys Ther, 9*(6), 798-812.

Drezner, J., Ulager, J., & Sennett, M. D. (2005). Hamstring muscle injuries in track and field athletes: a 3-year study at the Penn Relay Carnival [abstract]. *15*(5), 386.

Ekstrand, J., & Gillquist, J. (1983). Soccer injuries and their mechanisms: a prospective study. *Medicine and Science in Sports and Exercise, 15*(3), 267-270.

Ekstrand, J., Gillquist, J., Moller, M., Oberg, B., & Liljedahl, S. O. (1983). Incidence of soccer injuries and their relation to training and team success. *The American journal of sports medicine, 11*(2), 63-67.

Ekstrand, J., Hagglund, M., & Walden, M. (2011). Injury incidence and injury patterns in professional football: the UEFA injury study. *British Journal of Sports Medicine, 45*(7), 553-558.

Elliott, M. C., Zarins, B., Powell, J. W., & Kenyon, C. D. (2011). Hamstring muscle strains in professional football players: a 10-year review. *The American journal of sports medicine, 39*(4), 843-850.

Feeley, B. T., Kennelly, S., Barnes, R. P., Muller, M. S., Kelly, B. T., Rodeo, S. A., & Warren, R. F. (2008). Epidemiology of National Football League training camp injuries from 1998 to 2007. *The American journal of sports medicine, 36*(8), 1597-1603.

Freckleton, G., & Pizzari, T. (2013). Risk factors for hamstring muscle strain injury in sport: a systematic review and meta-analysis. *British Journal of Sports Medicine, 47*(6), 351-358.

Gabbe, B. J., Branson, R., & Bennell, K. L. (2006). A pilot randomised controlled trial of eccentric exercise to prevent hamstring injuries in community-level Australian Football. *Journal of science and medicine in sport / Sports Medicine Australia, 9*(1-2), 103-109.

Garrett, W. E., Jr. (1990). Muscle strain injuries: clinical and basic aspects. *Medicine and Science in Sports and Exercise, 22*(4), 436-443.

Garrett, W. E., Jr., Califf, J. C., & Bassett, F. H., 3rd. (1984). Histochemical correlates of hamstring injuries. *The American journal of sports medicine, 12*(2), 98-103.

Garrett, W. E., Jr., Safran, M. R., Seaber, A. V., Glisson, R. R., & Ribbeck, B. M. (1987). Biomechanical comparison of stimulated and nonstimulated skeletal muscle pulled to failure. *The American journal of sports medicine, 15*(5), 448-454.

Goldspink, D. F. (1978). The influence of passive stretch on the growth and protein turnover of the denervated extensor digitorum longus muscle. *Biochem J, 174*(2), 595-602.

Goldspink, G. (1999). Changes in muscle mass and phenotype and the expression of autocrine and systemic growth factors by muscle in response to stretch and overload. *J Anat, 194 (Pt 3)*, 323-334.

Guex, K., Daucourt, C., & Borloz, S. (2014). Validity and Reliability of Maximal Strength Assessment of Knee Flexors and Extensors Using Elastic Bands. *Journal of Sport Rehabilitation*.

Guex, K., Degache, F., Gremion, G., & Millet, G. P. (2013). Effect of hip flexion angle on hamstring optimum length after a single set of concentric contractions. *Journal of sports sciences, 31*(14), 1545-1552.

Guex, K., Fourchet, F., Loepelt, H., & Millet, G. P. (2012). Passive knee-extension test to measure hamstring tightness: influence of gravity correction. *Journal of Sport Rehabilitation, 21*(3), 231-234.

Guex, K., Gojanovic, B., & Millet, G. P. (2012). Influence of hip-flexion angle on hamstrings isokinetic activity in sprinters. *Journal of Athletic Training, 47*(4), 390-395.

Guex, K., Lugrin, V., Borloz, S., & Millet, G. P. (2014). Influence of a 6-weeks eccentric training on hamstring functional parameters and injury incidence in sprinters during a winter season. Soumis.

Guex, K., & Millet, G. P. (2013). Conceptual Framework for Strengthening Exercises to Prevent Hamstring Strains. *Sports medicine, 43*(12), 1207-1215.

Hagglund, M., Walden, M., & Ekstrand, J. (2006). Previous injury as a risk factor for injury in elite football: a prospective study over two consecutive seasons. *British Journal of Sports Medicine, 40*(9), 767-772.

Hagglund, M., Walden, M., & Ekstrand, J. (2013). Risk factors for lower extremity muscle injury in professional soccer: the UEFA Injury Study. *The American journal of sports medicine, 41*(2), 327-335.

Heiser, T. M., Weber, J., Sullivan, G., Clare, P., & Jacobs, R. R. (1984). Prophylaxis and management of hamstring muscle injuries in intercollegiate football players. *The American journal of sports medicine, 12*(5), 368-370.

Henderson, G., Barnes, C. A., & Portas, M. D. (2010). Factors associated with increased propensity for hamstring injury in English Premier League soccer players. *Journal of science and medicine in sport / Sports Medicine Australia, 13*(4), 397-402.

Higashihara, A., Nagano, Y., Ono, T., & Fukubayashi, T. (2014). Relationship between the peak time of hamstring stretch and activation during sprinting. *Eur J Sport Sci*, 1-6.

Hogervorst, T., & Vereecke, E. E. (2014). Evolution of the human hip. Part 2: muscling the double extension. EPub.

Iga, J., Fruer, C. S., Deighan, M., Croix, M. D., & James, D. V. (2012). 'Nordic' hamstrings exercise - engagement characteristics and training responses. *International journal of sports medicine, 33*(12), 1000-1004.

Jonhagen, S., Ericson, M. O., Nemeth, G., & Eriksson, E. (1996). Amplitude and timing of electromyographic activity during sprinting. *Scandinavian journal of medicine & science in sports, 6*(1), 15-21.

Kaminski, T. W., Wabbersen, C. V., & Murphy, R. M. (1998). Concentric versus enhanced eccentric hamstring strength training: clinical implications. *Journal of Athletic Training, 33*(3), 216-221.

Kilgallon, M., Donnelly, A. E., & Shafat, A. (2007). Progressive resistance training temporarily alters hamstring torque-angle relationship. *Scandinavian journal of medicine & science in sports, 17*(1), 18-24.

Kivi, D. M., Maraj, B. K., & Gervais, P. (2002). A kinematic analysis of high-speed treadmill sprinting over a range of velocities. *Medicine and Science in Sports and Exercise, 34*(4), 662-666.

Koulouris, G., & Connell, D. (2003). Evaluation of the hamstring muscle complex following acute injury. *Skeletal radiology, 32*(10), 582-589.

Kumazaki, T., Ehara, Y., & Sakai, T. (2012). Anatomy and physiology of hamstring injury. *International journal of sports medicine, 33*(12), 950-954.

Lenhart, R., Thelen, D., & Heiderscheit, B. (2014). Hip Muscle Loads During Running at Various Step Rates. *The Journal of orthopaedic and sports physical therapy*, 1-30.

Levinger, I., Goodman, C., Hare, D. L., Jerums, G., Toia, D., & Selig, S. (2009). The reliability of the 1RM strength test for untrained middle-aged individuals. *Journal of science and medicine in sport / Sports Medicine Australia, 12*(2), 310-316.

Liu, H., Garrett, W. E., Moorman, C. T., & Yu, B. (2012). Injury rate, mechanism, and risk factors of hamstring strain injuries in sports: A review of the literature. *J Sport Health Sci, 1*(2), 92-101.

Lunnen, J. D., Yack, J., & LeVeau, B. F. (1981). Relationship between muscle length, muscle activity, and torque of the hamstring muscles. *Physical Therapy, 61*(2), 190-195.

Lynn, R., Talbot, J. A., & Morgan, D. L. (1998). Differences in rat skeletal muscles after incline and decline running. *J Appl Physiol (1985), 85*(1), 98-104.

Mair, S. D., Seaber, A. V., Glisson, R. R., & Garrett, W. E., Jr. (1996). The role of fatigue in susceptibility to acute muscle strain injury. *The American journal of sports medicine, 24*(2), 137-143.

Malliaropoulos, N., Mendiguchia, J., Pehlivanidis, H., Papadopoulou, S., Valle, X., Malliaras, P., & Maffulli, N. (2012). Hamstring exercises for track and field athletes: injury and exercise biomechanics, and possible implications for exercise selection and primary prevention. *British Journal of Sports Medicine, 46*(12), 846-851.

Mann, R. A., & Hagy, J. (1980). Biomechanics of walking, running, and sprinting. *The American journal of sports medicine, 8*(5), 345-350.

Martínez-Ruiz, E., Mendiguchia, J., Rubio-Arias, J. A., Alcaraz, P. E., & Esparza-Ros, F. (2014). *Effect of a prevention program for hamstring strain injury on optimum length of the knee flexors.* Paper presented at the IOC World Conference on Prevention of Injury & Illness in Sport, Monaco.

McAllister, M. J., Hammond, K. G., Schilling, B. K., Ferreria, L. C., Reed, J. P., & Weiss, L. W. (2014). Muscle activation during various hamstring exercises. *Journal of strength and conditioning research / National Strength & Conditioning Association, 28*(6), 1573-1580.

Mendiguchia, J., Samozino, P., Martinez-Ruiz, E., Brughelli, M., Schmikli, S., Morin, J. B., & Mendez-Villanueva, A. (2014). Progression of mechanical properties during on-field sprint running after returning to sports from a hamstring muscle injury in soccer players. *International journal of sports medicine, 35*(8), 690-695.

Mjolsnes, R., Arnason, A., Osthagen, T., Raastad, T., & Bahr, R. (2004). A 10-week randomized trial comparing eccentric vs. concentric hamstring strength training in well-trained soccer players. *Scandinavian journal of medicine & science in sports, 14*(5), 311-317.

Mohamed, O., Perry, J., & Hislop, H. (2002). Relationship between wire EMG activity, muscle length, and torque of the hamstrings. *Clinical biomechanics, 17*(8), 569-579.

Morgan, D. L. (1990). New insights into the behavior of muscle during active lengthening. *Biophysical journal, 57*(2), 209-221.

Murphy, J. C., O'Malley, E., Gissane, C., & Blake, C. (2012). Incidence of injury in Gaelic football: a 4-year prospective study. *The American journal of sports medicine, 40*(9), 2113-2120.

Nagano, Y., Higashihara, A., Takahashi, K., & Fukubayashi, T. (2014). Mechanics of the muscles crossing the hip joint during sprint running. *Journal of sports sciences*, 1-7.

Nelson, R. T., & Bandy, W. D. (2004). Eccentric Training and Static Stretching Improve Hamstring Flexibility of High School Males. *Journal of Athletic Training, 39*(3), 254-258.

Novacheck, T. F. (1998). The biomechanics of running. *Gait & posture, 7*(1), 77-95.

Opar, D. A., Piatkowski, T., Williams, M. D., & Shield, A. J. (2013). A Novel Device Using the Nordic Hamstring Exercise to Assess Eccentric Knee Flexors Strength: A Reliability and Retrospective Injury Study. *The Journal of orthopaedic and sports physical therapy*.

Opar, D. A., Williams, M. D., & Shield, A. J. (2012). Hamstring strain injuries: factors that lead to injury and re-injury. *Sports medicine, 42*(3), 209-226.

Orchard, J., Marsden, J., Lord, S., & Garlick, D. (1997). Preseason hamstring muscle weakness associated with hamstring muscle injury in Australian footballers. *The American journal of sports medicine, 25*(1), 81-85.

Orchard, J., & Seward, H. (2002). Epidemiology of injuries in the Australian Football League, seasons 1997-2000. *British Journal of Sports Medicine, 36*(1), 39-44.

Orchard, J. W. (2012). Hamstrings are most susceptible to injury during the early stance phase of sprinting. *British Journal of Sports Medicine, 46*(2), 88-89.

Orchard, J. W., Seward, H., & Orchard, J. J. (2013). Results of 2 decades of injury surveillance and public release of data in the Australian football league. *The American journal of sports medicine, 41*(4), 734-741.

Petersen, J., Thorborg, K., Nielsen, M. B., Budtz-Jorgensen, E., & Holmich, P. (2011). Preventive effect of eccentric training on acute hamstring injuries in men's soccer: a cluster-randomized controlled trial. *The American journal of sports medicine, 39*(11), 2296-2303.

Pinniger, G. J., Steele, J. R., & Groeller, H. (2000). Does fatigue induced by repeated dynamic efforts affect hamstring muscle function? *Medicine and Science in Sports and Exercise, 32*(3), 647-653.

Posner, M., Cameron, K. L., Wolf, J. M., Belmont, P. J., Jr., & Owens, B. D. (2011). Epidemiology of Major League Baseball injuries. *The American journal of sports medicine, 39*(8), 1676-1680.

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

Proske, U., Morgan, D. L., Brockett, C. L., & Percival, P. (2004). Identifying athletes at risk of hamstring strains and how to protect them. *Clinical and experimental pharmacology & physiology, 31*(8), 546-550.

Schache, A. G., Blanch, P., Rath, D., Wrigley, T., & Bennell, K. (2002). Three-dimensional angular kinematics of the lumbar spine and pelvis during running. *Human movement science, 21*(2), 273-293.

Schache, A. G., Dorn, T. W., Blanch, P. D., Brown, N. A., & Pandy, M. G. (2012). Mechanics of the human hamstring muscles during sprinting. *Medicine and Science in Sports and Exercise, 44*(4), 647-658.

Schache, A. G., Wrigley, T. V., Baker, R., & Pandy, M. G. (2009). Biomechanical response to hamstring muscle strain injury. *Gait & posture, 29*(2), 332-338.

Schmitt, B., Tim, T., & McHugh, M. (2012). Hamstring injury rehabilitation and prevention of reinjury using lengthened state eccentric training: a new concept. *Int J Sports Phys Ther, 7*(3), 333-341.

Schünke, M., Schulte, E., & Schumacher, U. (2006). *Atlas d'anatomie Prométhée : Tome 1, Anatomie générale et système locomoteur* (J. Chevalier & R. Douard, Trans.). Paris: Maloine.

Seagrave, R. A., Perez, L., McQueeney, S., Toby, E. B., V., K., & Nelson, J. D. (2014). Preventive Effects of Eccentric Training on Acute Hamstring Muscle Injury in Professional Baseball. *Orthop J Sports Med, 2*.

Seward, H., Orchard, J., Hazard, H., & Collinson, D. (1993). Football injuries in Australia at the elite level. *The Medical journal of Australia, 159*(5), 298-301.

Seynnes, O. R., de Boer, M., & Narici, M. V. (2007). Early skeletal muscle hypertrophy and architectural changes in response to high-intensity resistance training. *J Appl Physiol (1985), 102*(1), 368-373.

Sugiura, Y., Saito, T., Sakuraba, K., Sakuma, K., & Suzuki, E. (2008). Strength deficits identified with concentric action of the hip extensors and eccentric action of the hamstrings predispose to hamstring injury in elite sprinters. *The Journal of orthopaedic and sports physical therapy, 38*(8), 457-464.

Sun, Y., Wei, S., Liu, Y., Zhong, Y., Fu, W., & Li, L. (2014). How Joint Torques Affect Hamstring Injury Risk in Sprinting Swing-Stance Transition. *Medicine and Science in Sports and Exercise.*

Thelen, D. G., Chumanov, E. S., Hoerth, D. M., Best, T. M., Swanson, S. C., Li, L., . . . Heiderscheit, B. C. (2005). Hamstring muscle kinematics during treadmill sprinting. *Medicine and Science in Sports and Exercise, 37*(1), 108-114.

Turner, A. N., Cree, J., Comfort, P., Jones, L., Chavda, S., Bishop, C., & Reynolds, A. (2014). Hamstring Strain Prevention in Elite Soccer Players. *Strength and Conditioning Journal, 36*(5), 10-20.

van Beijsterveldt, A. M., van de Port, I. G., Vereijken, A. J., & Backx, F. J. (2012). Risk Factors for Hamstring Injuries in Male Soccer Players: A Systematic Review of Prospective Studies. *Scandinavian journal of medicine & science in sports.*

Verrall, G. M., Kalairajah, Y., Slavotinek, J. P., & Spriggins, A. J. (2006). Assessment of player performance following return to sport after hamstring muscle strain injury. *Journal of science and medicine in sport / Sports Medicine Australia, 9*(1-2), 87-90.

Verrall, G. M., Slavotinek, J. P., Barnes, P. G., Fon, G. T., & Spriggins, A. J. (2001). Clinical risk factors for hamstring muscle strain injury: a prospective study with correlation of injury by magnetic resonance imaging. *British Journal of Sports Medicine, 35*(6), 435-439; discussion 440.

Wisdom, K. M., Delp, S. L., & Kuhl, E. (2014). Use it or lose it: multiscale skeletal muscle adaptation to mechanical stimuli. *Biomech Model Mechanobiol.*

Witvrouw, E., Danneels, L., Asselman, P., D'Have, T., & Cambier, D. (2003). Muscle flexibility as a risk factor for developing muscle injuries in male professional soccer players. A prospective study. *The American journal of sports medicine, 31*(1), 41-46.

Wood, S. A., Morgan, D. L., & Proske, U. (1993). Effects of repeated eccentric contractions on structure and mechanical properties of toad sartorius muscle. *The American journal of physiology, 265*(3 Pt 1), C792-800.

Woods, C., Hawkins, R., Hulse, M., & Hodson, A. (2002). The Football Association Medical Research Programme: an audit of injuries in professional football-analysis of preseason injuries. *British Journal of Sports Medicine, 36*(6), 436-441; discussion 441.

Woods, C., Hawkins, R. D., Maltby, S., Hulse, M., Thomas, A., Hodson, A., & Football Association Medical Research, P. (2004). The Football Association Medical Research Programme: an audit of injuries in professional football--analysis of hamstring injuries. *British Journal of Sports Medicine, 38*(1), 36-41.

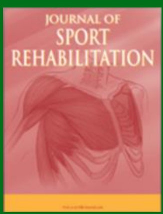
Worrell, T. W., Perrin, D. H., & Denegar, C. R. (1989). The influence of hip position on quadriceps and hamstring peak torque and reciprocal muscle group ratio values. *The Journal of orthopaedic and sports physical therapy, 11*(3), 104-107.

Yeung, S. S., Suen, A. M., & Yeung, E. W. (2009). A prospective cohort study of hamstring injuries in competitive sprinters: preseason muscle imbalance as a possible risk factor. *British Journal of Sports Medicine, 43*(8), 589-594.

Yu, B., Queen, R. M., Abbey, A. N., Liu, Y., Moorman, C. T., & Garrett, W. E. (2008). Hamstring muscle kinematics and activation during overground sprinting. *Journal of biomechanics, 41*(15), 3121-3126.

Chapitre 5. Articles

5.1. Article 1



Guex, K., Fourchet, F., Loepelt, H., & Millet, G. P. (2012). Passive knee-extension test to measure hamstring tightness: influence of gravity correction. *Journal of Sport Rehabilitation*, *21*(3), 231-234.

Abstract

Context: A passive knee-extension test has been shown to be a reliable method of assessing hamstring tightness, but this method does not take into account the potential effect of gravity on the tested leg. ***Objective:*** To compare an original passive knee-extension test with 2 adapted methods including gravity's effect on the lower leg. ***Design:*** Repeated measures. ***Setting:*** Laboratory. ***Participants:*** 20 young track and field athletes (16.6 ± 1.6 y, 177.6 ± 9.2 cm, 75.9 ± 24.8 kg). ***Intervention:*** Each subject was tested in a randomized order with 3 different methods: In the original one (M1), passive knee angle was measured with a standard force of 68.7 N (7 kg) applied proximal to the lateral malleolus. The second (M2) and third (M3) methods took into account the relative lower-leg weight (measured respectively by handheld dynamometer and anthropometrical table) to individualize the force applied to assess passive knee angle. ***Main outcome measures:*** Passive knee angles measured with video-analysis software. ***Results:*** No difference in mean individualized applied force was found between M2 and M3, so the authors assessed passive knee angle only with M2. The mean knee angle was different between M1 and M2 (68.8 ± 12.4 vs 73.1 ± 10.6, $P < .001$). Knee angles in M1 and M2 were correlated ($r = .93$, $P < .001$). ***Conclusions:*** Differences in knee angle were found between the original passive knee-extension test and a method with gravity correction. M2 is an improved version of the original method (M1) since it minimizes the effect of gravity. Therefore, we recommend using it rather than M1. ***Keywords:*** flexibility, thigh, hip.

Acknowledgments

This project was reviewed and approved by the institutional research and ethics committee of Aspetar, Qatar Orthopedic and Sports Medicine Hospital.

Introduction

Controversial relationships between hamstring tightness and injury prevalence are reported in the literature.[1,2] Nevertheless, hamstring flexibility remains one of the most common assessments performed in sports therapy. Several methods have been proposed to evaluate hamstring flexibility, including the sit-and-reach test,[3] different modifications of the original sit-and-reach test,[4] an active knee-extension test,[5] and finally a passive knee-extension test.[6,7] The latter test is designed to minimize the associated pelvic motion, to have an objective fixed end point, and to be convenient and quickly performed. The subject is supine on an examination table and the tested leg is positioned in 120°[6] or in 90°[7] of hip flexion (0° = hip in straight position). Then the knee is passively extended by applying a standardized force of 7 kg for women and 8 kg for men with a dynamometer located just proximal to the lateral malleolus.[6] When stabilized, the knee angle is measured with a goniometer.

This method has been shown to be reliable. In fact, no difference between the test–retest measures (r = .98) was found.[6,7] However, one may note that the method does not take into account the potential effect of gravity on the tested leg. Indeed, the closer to vertical it is, the lower the relative weight of the lower leg. As it was already shown in isokinetic testing, where the relative contribution of gravity to recorded torque values becomes increasingly large as the active torque generation decreases,[8] it is important to correct values of a passive knee-extension test biased by gravitational effects to obtain a more accurate assessment of hamstring tightness. Therefore, the purpose of the current study was to compare an adapted method including gravity's effect on the lower leg–foot complex with the original passive knee-extension test.

Methods

Participants

The subjects were 20 young male track and field athletes (16.6 ± 1.6 y, 177.6 ± 9.2 cm, 75.9 ± 24.8 kg) training in a national training center twice a day under the supervision of a coach in addition to their school time. Before data collection, all subjects were required to read and sign an informed consent approved by the local institutional review board.

Experimental design

Each subject was tested in a randomized order with the different passive knee-extension tests. Between tests, the subjects rested seated for 10 minutes.

Passive knee-extension test

In method 1 (M1), subjects were placed in the reference position: supine, the lumbar spine kept flat on the table, with the contralateral leg extended and the ipsilateral hip and knee flexed to 90° (Figure 1A). The hip was maintained in a neutral rotation position. Hamstring muscle tightness was measured with standard protocols: A force of 68.7 N (7 kg) was applied proximal to the lateral malleolus by the examiner using a handheld dynamometer (compact force gauge, Mecmesin, Slinfold, UK) to determine the passive knee angle (Figure 1B), 0° being the knee angle in the reference position and 90° being the extended knee. The angle was measured with video-analysis software (Dartfish Software, TeamPro, Fribourg, Switzerland).

The passive knee angle is easy to measure in adolescents since it requires them only to remain passive and relaxed. All measurements were video recorded and analyzed by the same investigator, with a good intratester reliability: intraclass coefficient, ICC (1, 1) = .80.

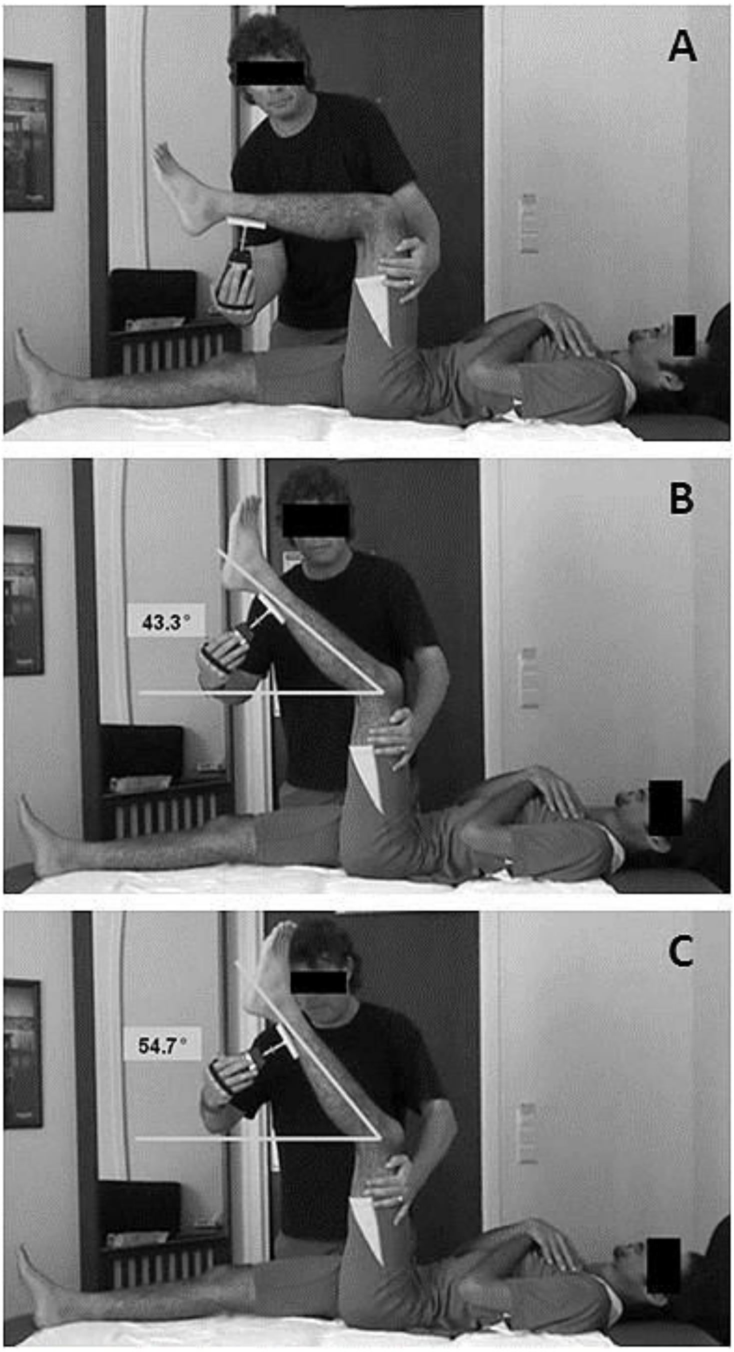


Figure 1. Visual representation of the video capture and angle measurement for each method. (A) Reference position of the passive knee-extension test. (B) Method 1 (0° = knee angle in the reference position and 90° = extended knee); for this subject, the passive knee angle is 43.3°. (C) Method 2; for this subject, the passive knee angle is 54.7°.

Passive knee-extension test with measured lower-leg weight

In method 2 (M2), in the reference position (Figure 1A), the handheld dynamometer was applied on the lower leg (proximal to the lateral malleolus) to determine its weight at this point (*WP*, N). After that, we assessed hamstring tightness in the same way as in M1 (with a 68.7-N force) to find the passive knee angle (α). To determine the applied force (*F*) to be added to the 68.7 N, we multiplied the cosine of alpha by the weight of the lower leg:

$$F = (\cos \alpha) \cdot WP$$

Finally, we evaluated the passive knee angle with the new applied force (68.7 + *F*). The video-analysis software was used to determine the angle for M2 (Figure 1C).

Passive knee-extension test with lower-leg weight determined from anthropometrical table

In method (M3), the subjects were weighed and measured (Holtain Ltd, Crosswell, Crymych, UK). Then, the weight (*W* = 6.1% of body weight), length (*L* = 28.5% of body size), and center-of-mass location (from the knee: 60.6% of the length of the lower leg–foot complex) of the lower leg–foot complex were determined from the anthropometrical table.[9] To determine the lower-leg weight at the dynamometer pressure point (WP_2; proximal to the lateral malleolus), we used the following formula:

$$WP_2 = [W \cdot (0.606 \cdot L)] / L$$

After that, hamstring tightness was assessed in the same way as in M1 with the 68.7 N of pushing to find the alpha (α) angle. To determine the applied force (F_2) to add to this 68.7 N we used the following formula:

$$F_2 = (\cos \alpha) \cdot WP_2$$

Each subject completed M3, but after statistical analysis (1-way repeated-measure analysis of variance [ANOVA] and a Tukey post hoc test), we did not find any difference between the individualized applied forces of M2 and M3 (79.4 ± 7.6 N for both M2 and M3), so we chose to evaluate passive hamstring flexibility only with M2 (see Discussion).

Statistical analysis

Results are presented as mean ± SD. Since the data were normally distributed, differences in force between the 3 methods were tested with an ANOVA and a Tukey post hoc test to localize the differences between means. Differences in knee angle between M1 and M2 were tested with a paired *t* test. Pearson product–moment correlations were used to identify significant relationships. Statistical significance was set at $P \leq .05$ (SigmaStat 11.0, Systat Software, Chicago, IL).

Results

Values of force and knee angle are reported in Table 1. The one-way repeated-measures ANOVA showed significant differences in the mean applied force between the 3 methods (F = 36.86, df = 2, $P < .001$). The Tukey post hoc test found significant differences between M2 and M1 ($P < .001$) and between M3 and M1 ($P < .001$), but, as mentioned in the Methods section, no difference was found between M2 and M3. Applied force for M2 was correlated to applied force for M3 ($r = .93$, $P < .001$). The mean knee angle was significantly different between M1 and M2 ($t = -3.98$, df = 19, $P < .001$). Knee angle for M1 was correlated to knee angle for M2 ($r = .93$, $P < .001$).

Table 1. Forces in M1, M2, and M3 and Knee Angles in M1 and M2.

	M1	M2	M3
Applied force, N			
mean ± SD	68.7 ± 0.0	79.4 ± 7.6 *	79.4 ± 7.6 *
minimum	68.7	69.5	69.7
maximum	68.7	94.7	92.0
range	0.0	25.3	22.3
Knee angle, °			
mean ± SD	68.8 ± 12.4	73.1 ± 10.6 *	NT
minimum	45.8	51.9	NT
maximum	87.0	88.1	NT
range	41.2	36.2	NT

Abbreviations: M1, method 1; M2, method 2; M3, method 3; NT, nontested.
*Significant differences with M1 ($P < .001$).

Discussion

The current study shows significant differences in passive knee angle between M2 and M1. The choice of the applied force in the original method was empirical. It was based on the feeling of the subjects and on an unpublished, preliminary study, where a linear relationship between the applied force (4–10 kg) and the knee angle was found.[6] To include gravity correction, we chose to add the relative weight of the lower leg–foot complex to the 68.7 N of the original method. This addition can explain the difference in passive knee angle between M1 and M2, but one may argue that M2 is a more accurate method for assessing passive hamstring flexibility.

This study also shows that the mean knee angle in M2 was well correlated with the mean knee angle in M1. This result is not surprising, given the repeated nature of M2 in regard to M1.

However, as shown in Table 1, since the range of knee angle is smaller with M2 than with M1, we speculated that a modified M2 (with a force added to a lower force than 68.7 N) would lead to a larger range of knee angle. This could potentially be a more discriminative method for assessing hamstring flexibility.

We did not assess passive hamstring flexibility with M3 for the following reason: The mean applied forces were not statistically different between M2 and M3 and were well correlated (r = .93, P < .001). In addition, we preferred M2 to M3 for its simplicity. In fact, M2 required less calculation and was easier and quicker, which is an important aspect for physiotherapists and researchers. It is not surprising to find the same force values for M2 and M3. In fact, in the reference position (Figure 1A), the passive structures of the knee (ligaments, articular capsule) and the thigh (tendons of hamstring and/or quadriceps muscles) are for the most part not in a stretch position. They influence to a negligible extent the relative weight of the lower leg–foot complex and therefore do not modify the weight obtained with M2.

Gravity correction is also an important factor when assessing populations with large differences in body dimensions, for example, in adolescents with various maturation status and body size (eg, in this study, a distance runner was 162.2 cm tall and weighed 41.3 kg, while a thrower was 183.3 cm tall and weighed 128.1 kg). One may assume that taking into account the weight of the lower leg relative to the angle would lead to a more precise and adapted measure of hamstring flexibility.

In practice, assessing passive knee extension with M2 is more complicated than with M1 because it involves assessing twice the same measure and calculating the cosine of alpha multiplied by the lower-leg weight. But M2 is an improved version of the original method (M1) since it minimizes the effect of gravity. Therefore, we recommend using it rather than M1.

References

1. Clark RA. Hamstring injuries: risk assessment and injury prevention. *Ann Acad Med Singapore*. 2008;37(4):341–346. PubMed

2. Worrell TW, Perrin DH. Hamstring muscle injury: the influence of strength, flexibility, warm-up, and fatigue. *J Orthop Sports Phys Ther*. 1992;16(1):12–18. PubMed

3. Wells KF, Dillon KE. The sit and reach: a test of back and leg flexibility. *Res Q*. 1952;23:115–118.

4. Baltaci G, Un N, Tunay V, Besler A, Gerceker S. Comparison of three different sit and reach tests for measurement of hamstring flexibility in female university students. *Br J Sports Med*. 2003;37(1):59–61. PubMed doi:10.1136/bjsm.37.1.59

5. Gajdosik R, Lusin G. Hamstring muscle tightness: reliability of an active-knee-extension test. *Phys Ther*. 1983;63(7):1085–1090. PubMed

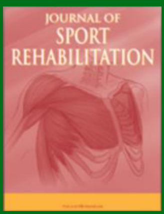
6. Fredriksen H, Dagfinrud H, Jacobsen V, Maehlum S. Passive knee extension test to measure hamstring muscle tightness. *Scand J Med Sci Sports*. 1997;7(5):279–282. PubMed doi:10.1111/j.1600-0838.1997.tb00153.x

7. Worrell TW, Perrin DH, Gansneder BM, Gieck JH. Comparison of isokinetic strength and flexibility measures between hamstring injured and noninjured athletes. *J Orthop Sports Phys Ther*. 1991;13(3):118–125. PubMed

8. Winter DA, Wells RP, Orr GW. Errors in the use of isokinetic dynamometers. *Eur J Appl Physiol Occup Physiol*. 1981;46(4):397–408. PubMed doi:10.1007/BF00422127

9. Winter DA. *Biomechanics and Motor Control of Human Movement*. 3rd ed. Hoboken, NJ: John Wiley and Sons; 2004.

5.2. Article 2



Guex, K., Daucourt, C., & Borloz, S. (2014). Validity and reliability of maximal strength assessment of knee flexors and extensors using elastic bands. *Journal of Sport Rehabilitation,* Epub ahead of print.

Abstract

Context: In the field of sport rehabilitation, an easy, valid and reliable assessment of maximal strength is crucial for an efficient muscular rehabilitation. Classically, it is performed on fitness equipments, which are not necessary available in the field. Thera-Band® has developed elastic bands with different resistances depending on the color of the band and on the percentage of stretch of this last. This may allow testing maximal strength. ***Objective:*** To determine validity and reliability of maximal strength assessment of knee flexors and extensors using elastic bands. ***Design:*** Reliability and validity study. ***Participants:*** 22 healthy participants (31.3 ± 7.0 y, 175.5 ± 8.5 cm, 70.7 ± 12.9 kg). ***Intervention:*** Participants performed two maximal strength assessments, separated by seven days, of knee flexors and extensors using elastic bands. After the second trial, a maximal concentric isokinetic test at $60°\cdot s^{-1}$ was performed. ***Main outcome measures:*** Correlations between one repetition maximum (1-RM) using elastic bands and peak torque (PT) on isokinetic dynamometer were used to determine the validity of the proposed method, while ICC, CV and SEM were used to determine the reliability between first and second trials. ***Results:*** The validity of the proposed method was found to be very high (r = .93 for both knee flexors and extensors). The relative reliability was found to be very high (ICC = .98 and .99 for knee flexors and extensors, respectively), while absolute reliability was also very satisfying (CV = 3.44% and 2.33%; SEM = 1.70 kg and 2.16 kg for knee flexors and extensors, respectively). ***Conclusions:*** Thera-Band® is a valid and reliable alternative to the use of fitness equipments to test maximal strength of knee flexors and extensors in healthy subjects. The ease of use, accessibility and low cost of elastic bands should allow regular assessment during the rehabilitation process. ***Keywords:*** maximal strength, hamstring, quadriceps.

Introduction

Recovering muscular strength is one of the most important factors in sport rehabilitation. In order to reach the defined goal (eg, maximal strength, hypertrophy), different protocols specifying the number of repetitions and sets, with a load selected in percentage of the maximal strength have been described.[1] During rehabilitation, this maximal strength may change rapidly and, thus should be tested repeatedly in order to adjust the loads. Therefore, an easy, valid and reliable assessment of maximal strength is crucial for an efficient muscular rehabilitation.

Isokinetic dynamometry, which has been shown to be valid and reliable, is considered as the "gold standard" method for assessing muscular strength.[2] However, availability of this evaluation system is limited mainly because of its important cost. On fitness equipments, maximal strength can be found using the one repetition maximum (1-RM) test. This is a valid and reliable method.[3] However, in the context of rehabilitation, this assessment could be inappropriate, since an attempt using maximum resistance is required. Therefore, repetitions to fatigue test has been proposed. This method uses a prediction equation to find the 1-RM through a submaximal testing based on the practically linear relationship between strength and anaerobic endurance for set up to 10 repetitions.[4] This method was shown to be accurate to predict 1-RM.[5]

Elastic bands are commonly used during rehabilitation for muscular strengthening, and are available in most rehabilitation centers. Thera-Band® has developed bands with different color-coded resistance levels (eg, yellow, red, green, blue, black, silver and gold). For each color, this resistance can be measured in kilogram depending on the percentage that the band is stretched from its resting length.[6] Regardless of how long the band is before it is stretched, the force produced at its stretched length depends on the percent elongation. Hence, as it is the case on fitness equipments, muscular strength could be assessed using elastic bands. Therefore, the aim of the present study was to determine the validity and reliability of maximal strength assessment of knee flexors and extensors using elastic bands in healthy subjects.

Methods

Participants

Twenty-two healthy recreational athletes (10 women, 12 men; 31.3 ± 7.0 y, 175.5 ± 8.5 cm, 70.7 ± 12.9 kg) were recruited for this study. The study was conducted according to the Declaration of Helsinki. Ethical approval was obtained from the local committee on human research. Participants signed an informed consent after explanation of the study protocol, data collection procedures and significance of the study objectives.

Procedures

The testing procedures were administered to all participants by the same investigator. During the first visit, maximal strength of knee flexors and extensors was assessed using elastic bands (Thera-Band GmbH, Hadamar, Germany). Then, a familiarization on an isokinetic dynamometer (Biodex System 2, Biodex Medical Systems, Shirley, New York, USA) was performed. Seven days after, maximal strength of knee flexors and extensors was assessed using elastic bands following the same procedure. Then, maximal isokinetic strength of knee flexors and extensors was assessed on the isokinetic dynamometer. Participants were all tested on their dominant side. Maximal strength testing using elastic bands and isokinetic dynamometer were both performed on the Biodex seat. The knee range of motion (ROM) was 90° for all assessments (i.e. between 0° and 90° of knee flexion). During all tests, participants were asked to fold their arms across their chest (Figure 1).

Figure 1. Maximal strength testing of knee flexors (A) and extensors (B) using elastic bands and isokinetic assessment of knee flexors and extensors in concentric at $60°\cdot s^{-1}$ (C). To assess knee flexors, the elastic band was fixed just proximal to the lateral malleolus of the participants and on the wooden bar ~90 cm above the knee and ~60 cm in front of this articulation. To assess knee extensors, the elastic band was fixed just proximal to the lateral malleolus of the participants and on the wooden bar ~40 cm below the knee and ~160 cm behind this articulation.

Maximal strength assessment using elastic bands

Thera-Band® elastic bands provide a consistent, linear, and predictable increase in resistance with elongation across all colors.[6] Regression equations were proposed to quantify this resistance in kilogram based on the percentage of elongation.[6] These equations were used to quantify the resistances "lifted" by the participants at the end of ROM. Prior to the testing period, 15 different elastic bands were prepared (Table 1).

Table 1. Resistances in kilogram of the prepared elastic bands for knee flexors and extensors maximal strength assessments. The resistances ranging from 16.6 to 56.9 kg for the knee flexors and from 22.9 to 77.1 kg for the knee extensors.

Thera-Band® color	Number of layers	Initial length, cm	Knee flexors		Knee extensors	
			Terminal length, %	Resistance, kg	Terminal length, %	Resistance, kg
Black	4	70	101	16.6	160	22.9
		65	116	18.2	180	25.0
		60	134	20.2	203	27.5
Silver	4	75	88	20.9	143	29.5
		70	101	23.0	160	32.2
		65	116	25.4	180	35.3
		60	134	28.2	203	38.9
		55	156	31.5	231	43.2
Gold	4	75	88	33.9	143	47.4
		70	101	37.2	160	51.7
		65	116	41.0	180	56.5
		60	134	45.4	203	62.3
		55	156	50.6	231	69.0
		50	181	56.9	264	77.1
		45	213	64.5	304	87.0

After a 10 min warm-up on a cycling ergometer (60 rpm, 80 watts), participants were placed on the Biodex seat. Stabilization straps were positioned across their chest, pelvis, and ipsilateral thigh. To assess knee flexors, the Biodex seat was facing a wooden bar, while it was facing away the wooden bar for testing the knee extensors (Figure 1, A-B).

One-RM of knee flexors and extensors was predicted using repetitions to fatigue test. Participants were asked to perform a maximum of repetitions with an intermediate resistance elastic band (ie, black color-coded Thera-Band®). If they succeeded to perform 10 repetitions, a greater resistance elastic band was selected for the next attempt. This procedure was repeated (maximum 5 attempts with 5 min rest between attempts) until the participant succeeded to perform 10 or less repetitions.[4] The following prediction equation was then used:[4]

$$1RM = \text{resistance in kg} / (1.0278 - [0.0278 \cdot \text{reps}])$$

Isokinetic assessment

The dynamometer was calibrated according to the manufacturer's recommendations and following the instructions for optimal reproducibility. The lever arm shin-pad was positioned just proximal to the lateral malleolus of the participants. During the first visit, participants performed a familiarization on the isokinetic dynamometer, which consisted of 10 concentric knee flexion-extensions at $60°\cdot s^{-1}$. At the end of the second trial, participants performed 5 maximum concentric knee flexion-extensions of the dominant leg at $60°\cdot s^{-1}$ (Figure 1, C). Peak torque (PT) value for each movement was considered as the greatest PT production over the 5 repetitions.

Statistical analysis

Mean and standard deviation (SD) values were calculated for all assessments. Validity of maximal strength assessments of knee flexors and extensors using elastic bands was explored by calculating Pearson's correlation coefficients between 1-RM of the second trial and concentric PT. As general rule, we considered correlation coefficients > .90 as very high, .70-.89 as high and .50-.69 as moderate.[7] Relative reliability of maximal strength assessments using elastic bands was calculated with the intraclass correlation coefficient (ICC) (2, 1) between the two trials. ICC values were interpreted in the same way as the Pearson's correlation coefficients. Absolute reliability was calculated with the coefficient of variation (CV). An analytical goal of < 10% was used to interpret CV values.[8] Absolute reliability was, moreover, assessed with the standard error of measurement (SEM),[9] which provide an estimate of measurement error. SEM values were then used to determine the minimal detectable change (MDC) to be considered "real".[9] Finally, paired *t* test was used to compare the 1-RM of the two trials. Significance was set at $P < .05$. Statistical analysis was performed with SigmaPlot 11.0 (Systat Software Inc., San Jose, CA).

Results

Results for validity and reliability are presented as mean ± SD in Table 2 and 3, respectively. The validity of the proposed method was found to be very high (*r* = .93 for both knee flexors and extensors). The relative reliability was found to be very high (ICC = .98 and .99 for knee flexors and extensors, respectively), while absolute reliability was also very satisfying (CV = 3.44% and 2.33%; SEM = 1.70 kg and 2.16 kg; MDC = 4.73 and 5.99 kg for knee flexors and extensors, respectively). Finally, 1-RM using elastic bands were significantly higher in the second trial than in the first trial for both knee flexors ($P < .001$) and extensors ($P < .05$).

Table 2. Validity of the maximal strength assessments using elastic bands compared to PT values obtained on the isokinetic dynamometer. Data are presented as mean ± SD.

	1-RM trial 2, kg	PT, Nm	Correlation coefficient	*P*-value
Knee flexors	58.1 ± 17.2	106.3 ± 24.6	.93	< .001
Knee extensors	75.1 ± 24.6	191.8 ± 47.7	.93	< .001

Abbreviations: 1-RM, one repetition maximum; PT, peak torque.

Table 3. Reliability of the maximal strength assessments using elastic bands. Data are presented as mean ± SD.

	1-RM trial 1, kg	1-RM trial 2, kg	ICC	CV, %	SEM, kg	MDC, kg
Knee flexors	56.1 ± 16.3	58.1 ± 17.2***	.98	3.44	1.70	4.73
Knee extensors	73.6 ± 24.0	75.1 ± 24.6*	.99	2.33	2.16	5.99

Abbreviations: 1-RM, one repetition maximum; ICC, intraclass correlation coefficient; CV, coefficient of variation; SEM, standard error of measurement; MDC, minimum difference considered to be real.

* $P < .05$, *** $P < .001$ for differences with trial 1.

Discussion

The results of this study demonstrated that using elastic bands is highly valid and reliable to assess maximal strength of knee flexors and extensors in healthy people. In order to minimize the risk of injuries, it was preferred to use the repetitions to fatigue test than a "direct" 1-RM assessment. Classically, this type of "indirect" assessment is performed on fitness equipments and is shown to be a valid method to predict 1-RM.[5] It has also been shown to be valid in regard to the "gold standard", since 8-RM test (ie, an alternative to the repetitions to fatigue test) performed on a leg extension curl was found to be highly correlated (.85) with PT at $60°\cdot s^{-1}$ on an isokinetic dynamometer.[10] This result is in line with our observations and suggests that the proposed maximal strength assessment using elastic bands is a valid method to assess maximal strength.

Both test-retest relative and absolute reliabilities of maximal strength assessment using elastic bands were found to be very satisfying. For knee flexors and extensors, ICC values were largely > .80, which was suggested to be acceptable for clinical work.[11] CV values indicated also a good reliability, since they were both largely lower than the analytical goal of 10%.[8] Finally, SEM values were both very low (~2 kg for both knee flexors and extensors). A previous investigation has found ICC values ≥ .97 between "direct" 1-RM on hamstring curl and leg extension curl in two separated trials.[3] This is in line with the results of the present study and suggests that using elastic bands to test maximal strength is highly reliable and allows finding 1-RM as well as using fitness equipments.

The present study has some limitations. Compare to the first trial, 1-RM in the second trial were significantly higher of 2.0 and 1.5 kg for knee flexors and extensors, respectively. This could be attributed to a learning effect. However, the differences are not clinically relevant, since they are lower than MDC (4.7 and 6.0 kg for knee flexors and extensors, respectively). Furthermore, testing was conducted on the knee flexors and extensors only. Further studies should concentrate on validity and reliability on other muscle groups.

In conclusion, the present study suggests that Thera-Band® is a valid and reliable alternative to the use of fitness equipments to test maximal strength of knee flexors and extensors in healthy subjects. The ease of use, accessibility and low cost of elastic bands should allow regular assessment during the rehabilitation process. Moreover, this study shows that elastic bands could be a relevant tool for resistance training, since a specific load could be easily chosen in percentage of 1-RM by selecting Thera-Band® color, number of layers and terminal length (Table1). With an appropriate number of repetitions and sets1, it is then possible to reach the defined goal (eg, development of maximal strength, hypertrophy, muscular endurance or power) using elastic bands. These lasts could be revenant in rehabilitation of injured athletes as well as in training of non-injured athletes for a large variety of muscles groups.

References

1. ACSM. American College of Sports Medicine position stand. Progression models in resistance training for healthy adults. *Med Sci Sports Exerc.* 2009;41(3):687-708.
2. Brown LE, Whitehurst M, Bryant JR, Buchalter DN. Reliability of the Biodex System 2 isokinetic dynamometer concentric mode. *Isokinetics and Exercise Science.* 1993;3:139-143.
3. Levinger I, Goodman C, Hare DL, Jerums G, Toia D, Selig S. The reliability of the 1RM strength test for untrained middle-aged individuals. *J Sci Med Sport.* 2009;12(2):310-316.
4. Brzycki M. Strength testing: predicting a one-rep max from repetitions to fatigue. *J Physical Educ Recrea Dance.* 1993;64:88-90.
5. LeSuer DA, McCormick JH, Mayhew JL, Wasserstein RL, Arnold MD. The accuracy of prediction equations for estimating 1-RM performance in the bench press, squat, and deadlift. *Journal of Strength and Conditioning Research.* 1997;11(4):211-213.
6. Page PA, Labbe A, Topp RV. Clinical force production of Thera-Band elastic bands. *J Orthop Sports Phys Ther.* 2000;30(1):A47-A48.
7. Munro BH. *Statistical methods for health care research.* 5 ed. New York: Lippincott Williams & Wilkins; 2005.
8. Stokes M. Reliability and repeatability of methods for measuring muscle in physiotherapy. *Physiother Pract.* 1985;1:71-76.
9. Weir JP. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. *J Strength Cond Res.* 2005;19(1):231-240.
10. Taylor JD, Fletcher JP. Correlation between the 8-repetition maximum test and isokinetic dynamometry in the measurement of muscle strength of the knee extensors: A concurrent validity study. *Physiotherapy theory and practice.* 2013;29(4):335-341.

11. Currier D. *Elements of research in physical therapy*. Baltimore: Williams and Wilkins; 1990.

5.3. Article 3

Guex, K., Gojanovic, B., & Millet, G. P. (2012). Influence of hip-flexion angle on hamstrings isokinetic activity in sprinters. *Journal of Athletic Training, 47*(4), 390-395.

Abstract

Context: Hamstrings strains are common and debilitating injuries in many sports. Most hamstrings exercises are performed at an inadequately low hip-flexion angle because this angle surpasses 70° at the end of the sprinting leg's swing phase, when most injuries occur. ***Objective:*** To evaluate the influence of various hip-flexion angles on peak torques of knee flexors in isometric, concentric, and eccentric contractions and on the hamstrings-to-quadriceps ratio. ***Design:*** Descriptive laboratory study. ***Setting:*** Research laboratory. ***Patients and other participants:*** Ten national-level sprinters (5 men, 5 women; age = 21.2 ± 3.6 years, height = 175 ± 6 cm, mass = 63.8 ± 9.9 kg). ***Intervention(s):*** For each hip position (0°, 30°, 60°, and 90° of flexion), participants used the right leg to perform (1) 5 seconds of maximal isometric hamstrings contraction at 45° of knee flexion, (2) 5 maximal concentric knee flexion-extensions at 60° per second, (3) 5 maximal eccentric knee flexion-extensions at 60° per second, and (4) 5 maximal eccentric knee flexion-extensions at 150° per second. ***Main outcome measure(s):*** Hamstrings and quadriceps peak torque, hamstrings-to-quadriceps ratio, lateral and medial hamstrings root mean square. ***Results:*** We found no difference in quadriceps peak torque for any condition across all hip-flexion angles, whereas hamstrings peak torque was lower at 0° of hip flexion than at any other angle ($P < .001$) and greater at 90° of hip flexion than at 30° and 60° ($P < .05$), especially in eccentric conditions. As hip flexion increased, the hamstrings-to-quadriceps ratio increased. No difference in lateral or medial hamstrings root mean square was found for any condition across all hip-flexion angles ($P < .05$). ***Conclusions:*** Hip-flexion angle influenced hamstrings peak torque in all muscular contraction types; as hip flexion increased, hamstrings peak torque increased. Researchers should investigate further whether an eccentric resistance training program at sprint-specific hip-flexion angles (70° to 80°) could help prevent hamstrings injuries in sprinters. Moreover, hamstrings-to-quadriceps ratio assessment should be standardized at 80° of hip flexion. ***Key words:*** injury prevention, eccentric exercises, length-tension relationship, hamstrings-to-quadriceps ratio, muscle strains.

Key points

- Hip-flexion angle influenced hamstrings peak torque in isometric, concentric, and eccentric contractions.
- As hip flexion increased, hamstrings peak torque and hamstrings-to-quadriceps ratio increased, suggesting hamstrings-to-quadriceps ratio norms should be defined for a given hip angle; we propose 80° of hip flexion.
- The efficiency of hamstrings strengthening exercises could be improved by controlling hip angle.

Introduction

Most hamstrings muscle strain injuries occur while running or sprinting.[1] Researchers have reported that hamstrings strain accounts for 50% of all muscular injuries in sprinters,[1] with an incidence varying from 10% (1-year follow-up) to 24% (2-year follow-up).[2,3] In addition, the hamstrings are the second most common injury site in team sports, but the incidence of injury can vary from one field position to the next. In rugby, the incidence is greater for backs than forwards, probably due to their greater acceleration, deceleration, and high-speed running demands.[4] In football, the speed-position players (ie, wide receivers, defensive secondary) are at elevated risk for injury.[5] In Australian Rules football, hamstrings muscle strain is the most frequent injury that results in time missed from participation.[6] In soccer, muscle strains represent 30% of the injuries, and 28% of these strains involve the hamstrings.[7]

During sprinting, the risk of injury is at its highest in the late swing phase and is higher for the biceps femoris than for the medial hamstrings.[8,9] From a structural point of view, sprint-related hamstrings tears affect mainly the passive components of muscle fibers (ie, tendon, myotendinous junction, or epimysium).[10,11] According to Garrett et al,[12] the higher risk of injury for the biceps femoris could be due to its specific architecture (ie, unique dual innervations, lateral distal insertion, shorter fiber length compared with the semitendinosus, increased pennation angle with knee flexion). From a kinematic point of view, the second half of the swing phase brings the hip into flexion at an angle of more than 70°, with the knee extending to less than 40° of flexion at a velocity greater than 1000° per second.[7,8,13–15] This hip angle of 70° to 80° is specific to sprinting (Figure A[a–c]). Because the hamstrings are biarticular muscles, the combination of hip flexion and knee extension induces a substantial hamstrings muscletendon stretch. This stretch is even more pronounced due to the contralateral hip extending at the same time; this hip extension prevents the pelvis from tilting posteriorly, which would decrease the hamstrings stretch. A slight pelvis oscillation around its average angular position has been reported over the running cycle.[16] Therefore, the late swing phase causes the semimembranosus, semitendinosus, and long head of the biceps femoris to be stretched by 7.4%, 8.1%, and 9.5%, respectively, beyond their upright lengths.[8] The work of the hamstrings at this point is negative, and the electromyographic (EMG) activity shows peak activities in the medial biarticular hamstrings (MH) and lateral biarticular hamstrings (LH).[8,14,15,17] In summary, this active lengthening contraction in a stretch position at a high velocity during the late swing phase of the sprinting gait cycle corresponds to the time of highest injury risk for the hamstrings (ie, mainly the biceps femoris).

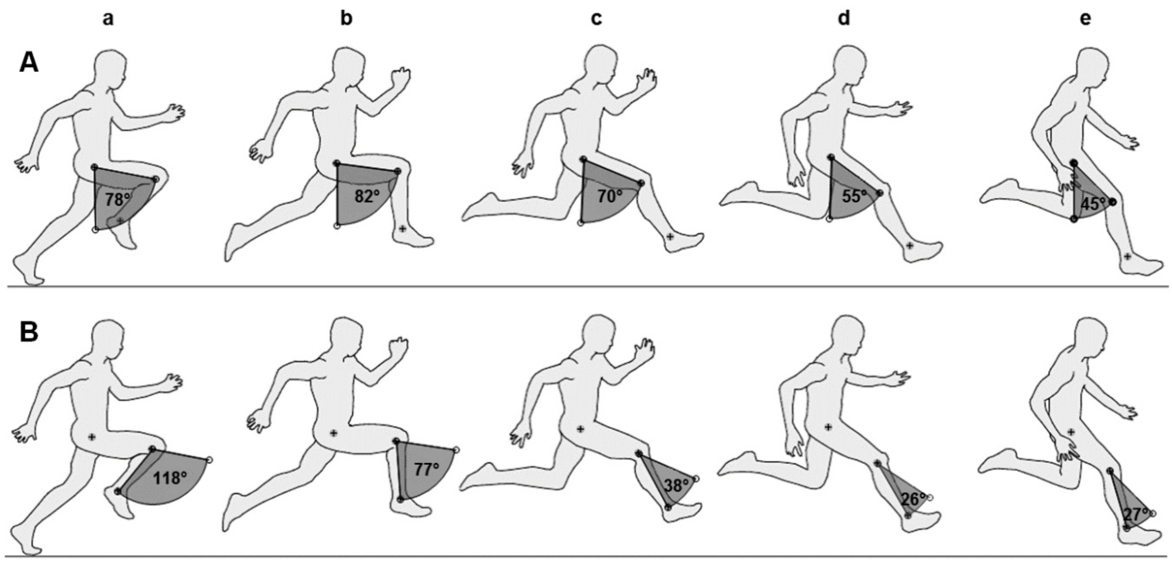


Figure. A, Hip flexions, and B, knee flexions, at about [a]75%, [b]80%, [c]85%, [d]90%, and [e]95% of the gait cycle of a world-class sprinter during a 100-m sprint. Letters a to c correspond with the specific hip-flexion position during sprinting. To determine elongation stress on hamstrings, subtract the angle in B (amount of knee flexion) from A (amount of hip flexion); a higher positive value indicates more elongation.

Current hamstrings injury-prevention programs are based on eccentric training. It has been shown to be an efficient method to increase strength and the hamstrings-to-quadriceps (H:Q) ratio, modify optimal hamstrings length (ie, angle of maximal peak torque), and eventually prevent injuries.[18–22] However, most of these investigators have used training methods or devices with either no hip flexion (eg, Nordic hamstrings exercise)[20] or nonspecified flexion (eg, yo-yo flywheel ergometer).[18] Moreover, probably the most-used hamstrings strength device is the prone hamstrings curl, which positions the hip at a nonspecific angle regarding sprinting biomechanics. In fact, during all these "classic" strength exercises, the hamstrings muscle-tendon complex is not stretched to the extent it is at the end of the swing phase (Figure).

As mentioned, the hip is in a flexed position during the late swing phase. Given the biarticular nature of the hamstrings, this hip-flexion position influences muscle activity. Several researchers[23–26] have shown that both isometric and concentric knee-flexion torques are greater when the hip is flexed (seated) rather than extended (supine). However, none of these authors has explored the influence of hip-flexion angle on hamstrings peak torque during eccentric contraction. Worrell et al[26] investigated the influence of hip flexion on H:Q ratio and found a greater ratio in the seated than prone position. Most H:Q ratio assessments are performed in a seated position (ie, between 70° and 90° of hip flexion). To reliably compare individuals, we need a consensus on a more precise hip-flexion angle for isokinetic evaluation. This consensus exists already for the angular velocity and the contraction mode.[27]

Therefore, the purpose of our study was to evaluate the influence of various hip-flexion angles on peak torques of knee flexors in isometric, concentric, and eccentric contractions and on H:Q ratio. A better understanding of the role of hip-flexion angle in hamstrings activity is required for improving hamstrings strength training and testing regarding the specifics of the sprinting gait cycle.

Methods

Participants

Ten national-level sprinters (5 women, 5 men; age = 21.2 ± 3.6 years, height = 175 ± 6 cm, mass = 63.8 ± 9.9 kg) volunteered for this study. All were recruited at the local track-and-field club. To be included, participants had to be short-track (100 m, 110-m hurdles, 200 m) or long-track (400 m or 400-m hurdles) sprinters and to have had no injury in the 3 months before the study. Participants provided written informed consent, and the study was approved by the faculty of Biology and Medicine, University of Lausanne.

Experimental design

Participants were tested in a temperature-controlled laboratory and were instructed not to exercise in the 48 hours before the study. After preparation for EMG recordings, they performed a 10-minute warm-up on a cycling ergometer. Next, they were seated correctly on an isokinetic dynamometer (Biodex System 2; Biodex Medical Systems, Shirley, NY). The distal portion of the dynamometer arm was strapped proximal to the ankle joint, and the axis of rotation at the knee was aligned with the lateral femoral condyle of the knee. The thigh was stabilized. The back support of the Biodex was positioned to fix the hip angle of the participants in the adequate articular amplitude. Participants were secured on the seat with stabilization straps so they would be as stable as possible during the whole assessment. For each hip-flexion angle (0°, 30°, 60°, 90°), participants performed (1) 5 seconds of maximal isometric hamstrings contraction of the right leg at 45° of knee flexion (ISO), (2) 5 maximal concentric knee flexion-extensions of the right leg at 60° per second (CON60), (3) 5 maximal eccentric knee flexion-extensions of the right leg at 60° per second (ECC60), and (4) 5 maximal eccentric knee flexion-extensions of the right leg at 150° per second (ECC150). They rested for 4 minutes between sets. Two sets of measures were performed at the same time of day; the first session assessed hip-flexion angles of 0° and

60°, and the second 14 days later assessed hip-flexion angles of 30° and 90°. Assessment order was not randomized.

Quadriceps and hamstrings peak torques were measured by the isokinetic dynamometer in ISO (hamstrings only), CON60, ECC60, and ECC150 at the various hip-flexion angles. Electromyographic data for the LH and MH were recorded (Myomonitor III; Delsys Inc, Boston, MA) by using surface EMG electrodes that had a DE-2.1 single-differential parallel-bar configuration with an interelectrode distance of 10 mm, bandwidth of 20 to 450 Hz, and a common mode rejection ratio of 80 dB per decade. The EMG electrodes were attached lengthwise over the muscle belly according to the recommendations for sensor locations on individual muscles developed by the Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles project.[28] The position of the electrodes was marked on the skin so that they could be fixed in the same place at the second set of measurements. The reference electrode was placed on the right patella. Low impedance (< 5 kΩ) of the skin electrode was obtained by abrading the skin with emery paper and cleaning it with alcohol.[29] The root mean square (RMS) was calculated over a 500-millisecond interval around the peak torque value (ie, 250 milliseconds before and 250 milliseconds after the peak torque) for each muscle.

Statistical analysis

The data were distributed normally. Peak torques and RMS were compared with a 2-way (hip-flexion angle [0°, 30°, 60°, 90°] by condition [ISO, CON60, ECC60, ECC150]) analysis of variance (ANOVA) with repeated measures. We used a Tukey post hoc test to localize the differences between means. The α level was set at .05. We used SigmaPlot (version 11.0; Systat Software, Inc, San Jose, CA) to analyze the data.

Results

Results are presented in the Table as mean ± standard deviation.

Table. Hamstrings and Quadriceps Peak Torques, Hamstrings-to-Quadriceps Ratio, Lateral and Medial Hamstrings Electromyographic Activity at Various Hip-Flexion Angles and Conditions (Mean ± SD).

	Hip Flexion Angle			
Variable	0°	30°	60°	90°
Hamstrings peak torque, Nm				
ISO	62.0 ± 15.8	88.8 ± 18.2[a,b]	96.4 ± 26.8[a,b]	110.1 ± 26.3[a]
CON60	69.3 ± 15.7	90.6 ± 19.4[a,b]	94.8 ± 24.6[a]	103.7 ± 25.8[a]
ECC60	80.1 ± 15.7[c]	102.1 ± 21.5[a,b,d,e]	109.3 ± 21.3[a,b,d,f]	121.3 ± 21.3[a,d,g]
ECC150	84.5 ± 18.9[c,f]	102.5 ± 17.5[a,e,h,i]	114.1 ± 27.8[a,c,g,h]	128.7 ± 29.3[a,c,g]
Quadriceps peak torque, Nm				
CON60	167.8 ± 29.4	182.1 ± 34.8	182.4 ± 33.4	191.1 ± 46.3
ECC60	220.0 ± 57.1[g]	222.4 ± 60.4[f]	225.2 ± 56.5[f]	225.6 ± 78.9[e]
ECC150	211.6 ± 52.3[f]	221.0 ± 66.3[e]	224.9 ± 58.6[f]	220.4 ± 75.1
Hamstrings-to-quadriceps ratio				
$H_{con60}:Q_{con60}$	0.41 ± 0.04	0.50 ± 0.06[j]	0.52 ± 0.07[j]	0.55 ± 0.08[j]
$H_{ecc60}:Q_{con60}$	0.48 ± 0.08[k]	0.56 ± 0.06[h,j,k]	0.60 ± 0.09[j,l]	0.65 ± 0.10[j,l]
Lateral hamstrings root mean square, μV				
ISO	215.7 ± 77.8	225.7 ± 103.9[b]	194.9 ± 94.3	160.6 ± 76.2
CON60	285.8 ± 141.7[d]	239.6 ± 102.1	218.8 ± 105.0	219.1 ± 122.1[d]
ECC60	214.2 ± 105.7[e]	198.4 ± 86.5	194.7 ± 85.2	161.5 ± 62.9
ECC150	193.2 ± 66.4[f]	176.9 ± 46.5[e]	171.4 ± 105.7[e]	160.7 ± 73.3[e]
Medial hamstrings root mean square, μV				
ISO	263.1 ± 122.9	230 ± 54.5	203.3 ± 88.3	166.4 ± 46.5
CON60	240.0 ± 84.1	219.1 ± 73.3	215.9 ± 78.3	184.0 ± 24.2
ECC60	235.2 ± 140.4	215.0 ± 115.3	177.4 ± 73.3	197.0 ± 55.9
ECC150	206.1 ± 110.1	160.2 ± 72.2	174.5 ± 113.8	188.0 ± 64.0

Abbreviations: CON60 indicates maximal concentric knee flexion-extensions of the right leg at 60° per second; ECC60, maximal eccentric knee flexion-extensions of the right leg at 60° per second; ECC150, maximal eccentric knee flexion-extensions of the right leg at 150° per second; ISO, maximal isometric hamstrings contraction of the right leg at 45° of knee flexion.

[a] Indicates different from 0° ($P < .001$), [b] Indicates different from 90° ($P < .05$), [c] Indicates different from ISO ($P < .001$), [d] Indicates different from ISO ($P < .05$), [e] Indicates different from CON60 ($P <$

.05), [f] Indicates different from CON60 (P < .01), [g] Indicates different from CON60 (P < .001), [h] Indicates different from 90° (P < .01), [i] Indicates different from ISO (P < .01), [j] Indicates different from 0° (P < .01), [k] Indicates different from $H_{con60}:Q_{con60}$ (P < .05), [l] Indicates different from $H_{ecc60}:Q_{con60}$ (P < .01).

Peak torque

We found differences among hip angles ($F_{3,9}$ = 68.163, P < .001). In each condition, hamstrings peak torque was lower at 0° of hip flexion than at any other angle (P < .001). Hamstrings peak torque was greater at 90° of hip flexion than at 30° and 60° (P < .05) except in CON60, where peak torques at 60° and 90° were not different (P = .20). We found differences among conditions ($F_{3,9}$ = 25.596, P < .001). At each hip-flexion angle, hamstrings peak torque was greater in ECC60 and ECC150 than in ISO and CON60 (P < .05) except at 0°, where peak torque in ECC60 and CON60 were not different (P = .052). At each hip-flexion angle, we found no difference between ECC60 and ECC150 (P > .05).

In each condition, we found no difference in quadriceps peak torque across all hip-flexion angles ($F_{3,9}$ = 0.724, P = .55). We found differences among conditions ($F_{2,9}$ = 11.556, P < .001). At each hip-flexion angle, quadriceps peak torque was greater in ECC60 and ECC150 than in CON60 (P < .05) except at 90°, where peak torques in ECC150 and CON60 (P = .06) were not different. At each hip-flexion angle, we found no difference between ECC60 and ECC150 (P > .05).

Hamstrings-to-quadriceps ratio

We found differences among hip angles ($F_{3,9}$ = 19.867, P < .001). At 0° of hip flexion, the concentric hamstrings-to-concentric quadriceps ratio at 60° per second ($H_{con60}:Q_{con60}$ ratio) was lower than at the other angles (P < .01). Similarly, at 0° of hip flexion, the eccentric hamstrings-to-concentric quadriceps ratio at 60° per second (H_{ecc60}:Q_{con60} ratio) was lower than at the other angles ($P < .01$). The H_{ecc60}:Q_{con60} ratio was greater at 90° than at 30° of hip flexion ($P < .01$). We found differences among conditions ($F_{1,9} = 14.913$, $P = .004$). At each hip-flexion angle, the H_{ecc60}:Q_{con60} ratio was greater than the H_{con60}:Q_{con60} ratio ($P < .05$).

Root mean square of muscle activation

We found no difference in RMS of the LH across the range of hip-flexion angles ($F_{3,9} = 5.455$, $P = .006$) except in ISO, where 30° of hip flexion produced greater RMS of hip flexion than 90° produced ($P = .01$). We found differences among conditions ($F_{3,9} = 7.484$, $P < .001$). At each hip-flexion angle, RMS of the LH was lower in ECC150 than in CON60 ($P = 01$). In addition, RMS of the LH at 0° was also lower in ECC60 than in CON60 ($P < .01$). At 0° and 90°, RMS of the LH was greater in CON60 than in ISO ($P = .02$ and $P = .046$, respectively). At each hip-flexion angle, no differences in RMS of the MH were found among any conditions ($F_{3,9} = 1.110$, $P = .37$).

Discussion

We examined the force produced by hamstrings and quadriceps muscles in various contraction modes and hip-flexion angles. Our main finding was that as the hip was flexed more, the hamstrings peak torque increased, regardless of the contraction regimes or isokinetic velocities for which we tested. For the isometric or concentric contractions at 60° per second, our results were in agreement with findings reported in the literature.[23–26] However, no researchers have examined torque and muscle activation in eccentric contractions while introducing another factor, specifically hip-flexion angle. We believe that assessing muscular variables at a hip-flexion angle of more than 60° is relevant because it corresponds with the actual position of the joint at the time when hamstrings activity and resistance are critical (ie, at the end of the swing phase of the sprinting legs). Our study showed that for both angular velocities (60° and 150° per second), eccentric peak torque of the hamstrings was higher in a stretched and lengthened position than in a shortened one. In other words, when the hip is flexed, hamstrings are lengthened and develop more eccentric torque. Researchers know that skeletal muscle fibers have an optimal length to produce the largest contraction force; it is neither too long nor too short. A muscle fiber increases its contraction force when stretched to its optimal length, beyond which it loses several actin-myosin bridges and the potential force generated decreases.[30] When stretched even farther, passive structures start to play a major role and increase their tensile force. Net tensile force of the muscle fiber is the sum of tensile forces in passive structures and the force of muscle-fiber contraction. Equally for each condition, our results showed that the hamstrings muscle can produce the largest knee-flexor torque when it is lengthened through additional hip flexion. At the largest hip flexion (90°), we observed that the hamstrings muscle-tendon complex was not lengthened beyond the physiologic optimal length because torque did not decrease compared with lower levels of hip flexion.

For all conditions, we observed no difference in quadriceps peak torque between different hip-flexion positions. These results contrast with those of Worrell et al,[26] who observed that concentric contractions at 60°, 180°, and 240° per second induced larger quadriceps peak torque when the hip was at 110° of flexion than at 10°. Our results are in line with those of Bohannon et al[23] who reported no difference in concentric quadriceps peak torque at 60° per second from 30° to 85° of hip flexion. We think that this lack of influence of hip-flexion angle could be explained by the fact that the quadriceps muscle is predominantly monoarticular (except for the rectus femoris), but the hamstrings muscle is biarticular. Thus, hip flexion influences to a lesser extent the passive stretch component of the quadriceps and, consequently, the torque level during knee extension.

The finding that hamstrings and quadriceps peak torques in ECC60 and ECC150 were greater than in ISO and CON60 was expected. The finding that hamstrings and quadriceps peak torques in ECC60 and ECC150 were greater than in ISO and CON60 was expected. They were also similar between ECC60 and ECC150. This is in line with the literature; the torque-velocity relationship for hamstrings eccentric contractions generally shows no or little difference in strength among different angular velocities. For example, Higashihara et al[31] reported no differences among hamstrings eccentric peak torques at 60°, 180°, and 300° per second.

We also showed that hip position influences both the H_{con60}:Q_{con60} ratio and the H_{ecc60}:Q_{con60} ratio. These results are consistent with those of Worrell et al,[26] who suggested that hip flexion was a confounding factor in the H:Q ratio assessment similar to the angular velocity or the contraction mode.[27] Because we found that hip angle directly influenced hamstrings but not quadriceps peak torque, we were not surprised to find that hip position also influenced H:Q ratio. These findings suggest that a specific hip-flexion position should be used to assess H:Q ratio, and such a standardized hip flexion would allow reliable interindividual comparison of this ratio.

Therefore, to be specific for sprinting biomechanics, we propose standardizing the hip angle at 80° of flexion during the H:Q ratio assessment (Figure A[a–c]).

One other part of our investigation included EMG activity measurements during the trials. We reported that the amount of hip flexion does not influence medial and lateral hamstrings EMG activity. This is consistent with the findings of Mohamed et al,[25] whereas Lunnen et al[24] showed greater hamstrings EMG activity at a larger hip-flexion angle. We believe that the lack of greater EMG signal with hip flexion points to the involvement of passive components to enhance hamstrings peak torque in this stretched position.

Researchers have shown that eccentric strengthening induces a shift in the length-tension relationship of muscle fibers[19,22] and an increase in the number of serial sarcomeres.[32,33] To date, investigators studying the influence of eccentric strengthening (with either the Nordic hamstrings exercise or the yo-yo flywheel ergometer) on strength, H:Q ratio, or injury prevention have not mentioned hip-flexion angle. Actually, these exercises were performed at a nonspecific angle, which does not correspond with the actual position at the end of the swing phase in sprinting.[18,20] Our findings are of interest in injury prevention. Indeed, controlling hip flexion from 70° to 80° during a hamstrings eccentric strengthening program would positively influence sarcomere length, bring additional effects on the passive components of the muscles, and provide a more adequate strengthening stimulus. Such strengthening of the lengthened hamstrings could be beneficial for injury prevention because we know that hamstrings tears mainly affect the passive components, such as the myotendinous junction or the epimysium.[34]

In practice, using a hamstrings strengthening device functioning with a hip-flexion angle greater than 60° might have additional potential benefits. Greater weight loads could be applied during knee flexion when using this type of device than when using a device without hip flexion, such as the lying hamstrings curl. We believe that optimal hamstrings strengthening for injury-prevention purposes should include the following features: on the one hand, an eccentric component with the hip flexed at the sprint-specific angle of 80° to 90°, in which position a higher peak torque can be generated and which would allow higher loads during training (greater resistance to knee flexion), and on the other hand, a concentric component because we have shown greater EMG activation of the LH in CON60 than ECC150. Therefore, combining concentric and eccentric stimuli during hamstrings strength training would be more effective in maintaining a high level of muscle innervation.

Moreover, our protocol might be used as a screening tool. Investigators could conduct studies in which the results of an established hamstrings strength test procedure for athletes in these positions and at these speeds could be compared with their injury rates and types over the course of a season. If predictive test results can be found for injury risk, specific preventive measures and strengthening exercises should be introduced. The speed of contraction and the strength at end-range elongation also are relevant predictors of hamstrings strains. However, for clinical use, we think that evaluating peak torque is more convenient for assessing how strength is influenced by hip-flexion angle and whether test results are a good predictor of injury risk.

In future studies, it would be interesting to assess how an eccentric strength-training program that includes this specific hip-flexion angle (70° to 80°) and peak torque as an identified risk factor for injury influences the angle of peak torque.[35] Even if this eccentric program already has been shown to effectively increase the angle of peak torque[21] and decrease injury rates,[18,36,37] we believe that it could be more effective if hip flexion was incorporated, which would add positive effects on passive hamstrings components.

Our study had some limitations. First, we did not test high-velocity eccentric contraction due to technical constraints. The Biodex System 2 only allowed us to assess a velocity up to 150° per second in eccentric mode. However, as mentioned, hamstrings peak torque does not change for velocities from 60° to 300° per second.[31] Second, participants were positioned with both hips at the same angular position, which is not what happens during the late swing phase of the running cycle. In addition, the pelvis of each participant was positioned in more posterior tilt than occurs during running, which would have reduced the lengthening stretch of the hamstrings during the tests. Third, we chose not to randomize the hip positions between the 2 sets. This did not seem to influence our results. In fact, values of peak torques and H:Q ratios at 30° and 90° of hip flexion were coherent with those at 0° and 60°. Although we noted no difference between hamstrings peak torques at 60° and 30° of hip flexion, we found a trend toward higher values at the higher hip flexion. Fourth, given a relatively large standard deviation, the interpretation of RMS data is debatable. In our view, EMG results are relevant as a control variable, showing that muscle activation is not different. Fifth, one of our participants had a hamstrings strain about 2 years before the study. We cannot exclude that an inadequate rehabilitation could have negatively affected the hamstrings peak torque assessment for this participant.

Conclusions

Hip-flexion angle influenced hamstrings peak torque in isometric, concentric, and eccentric isokinetic contractions. As hip flexion increased, hamstrings peak torque and H:Q ratio increased. This suggests that the H:Q ratio norms should be defined for a given hip angle. In addition, the efficiency of hamstrings-strengthening exercises could be improved by controlling hip angle. Whether a newly defined eccentric resistance-training program at a sprint-specific hip-flexion angle (70° to 80°) can better prevent hamstrings injuries in sprinters remains to be addressed, but our results lead us to believe that the perspective is worthwhile.

References

1. Agre JC. Hamstring injuries: proposed aetiological factors, prevention, and treatment. *Sports Med*. 1985;2(1):21–33.
2. Sugiura Y, Saito T, Sakuraba K, Sakuma K, Suzuki E. Strength deficits identified with concentric action of the hip extensors and eccentric action of the hamstrings predispose to hamstring injury in elite sprinters. *J Orthop Sports Phys Ther*. 2008;38(8):457–464.
3. Yamamoto T. Relationship between hamstring strains and leg muscle strength: a follow-up study of collegiate track and field athletes. J Sports Med Phys Fitness. 1993;33(2):194–199.
4. Brooks JH, Fuller CW, Kemp SP, Reddin DB. Epidemiology of injuries in English professional rugby union, part 2: training injuries. Br J Sports Med. 2005;39(10):767–775.
5. Elliott MC, Zarins B, Powell JW, Kenyon CD. Hamstring muscle strains in professional football players: a 10-year review. Am J Sports Med. 2011;39(4):843–850.
6. Seward H, Orchard J, Hazard H, Collinson D. Football injuries in Australia at the elite level. Med J Aust. 1993;159(5):298–301.
7. Volpi P, Melegati G, Tornese D, Bandi M. Muscle strains in soccer: a five-year survey of an Italian major league team. Knee Surg Sports Traumatol Arthrosc. 2004;12(5):482–485.
8. Thelen DG, Chumanov ES, Hoerth DM, et al. Hamstring muscle kinematics during treadmill sprinting. Med Sci Sports Exerc. 2005;37(1):108–114.
9. Chumanov ES, Schache AG, Heiderscheit BC, Thelen DG. Hamstrings are most susceptible to injury during the late swing phase of sprinting. Br J Sports Med. 2012;46(2):90.
10. Askling CM, Tengvar M, Saartok T, Thorstensson A. Acute first-time hamstring strains during high-speed running: a longitudinal study including clinical and magnetic resonance imaging findings. Am J Sports Med. 2007;35(5):197–206.

11. Koulouris G, Connell D. Evaluation of the hamstring muscle complex following acute injury. Skeletal Radiol. 2003;32(10):582–589.

12. Garrett WE Jr, Rich FR, Nikolaou PK, Vogler JB III. Computed tomography of hamstring muscle strains. Med Sci Sports Exerc. 1989;21(5):506–514.

13. Schache AG, Wrigley TV, Baker R, Pandy MG. Biomechanical response to hamstring muscle strain injury. Gait Posture. 2009;29(2):332–338.

14. Chumanov ES, Heiderscheit BC, Thelen DG. The effect of speed and influence of individual muscles on hamstring mechanics during the swing phase of sprinting. J Biomech. 2007;40(16):3555–3562.

15. Kivi DM, Maraj BK, Gervais P. A kinematic analysis of high-speed treadmill sprinting over a range of velocities. Med Sci Sports Exerc. 2002;34(4):662–666.

16. Schache AG, Blanch P, Rath D, Wrigley T, Bennell K. Threedimensional angular kinematics of the lumbar spine and pelvis during running. Hum Mov Sci. 2002;21(2):273–293.

17. Yu B, Queen RM, Abbey AN, Liu Y, Moorman CT, Garrett WE. Hamstring muscle kinematics and activation during overground sprinting. *J Biomech*. 2008;41(15):3121–3126.

18. Askling C, Karlsson J, Thorstensson A. Hamstring injury occurrence in elite soccer players after preseason strength training with eccentric overload. *Scand J Med Sci Sports*. 2003;13(4):244–250.

19. Brughelli M, Nosaka K, Cronin J. Application of eccentric exercise on an Australian Rules football player with recurrent hamstring injuries. *Phys Ther Sport*. 2009;10(2):75–80.

20. Mjlsnes R, Arnason A, Osthagen T, Raastad T, Bahr R. A 10-week randomized trial comparing eccentric vs. concentric hamstring strength training in well-trained soccer players. *Scand J Med Sci Sports*. 2004;14(5):311–317.

21. Brockett CL, Morgan DL, Proske U. Human hamstring muscles adapt to eccentric exercise by changing optimum length. *Med Sci Sports Exerc.* 2001;33(5):783–790.

22. Brughelli M, Mendiguchia J, Nosaka K, Idoate F, Arcos AL, Cronin J. Effects of eccentric exercise on optimum length of the knee flexors and extensors during the preseason in professional soccer players. *Phys Ther Sport.* 2010;11(2):50–55.

23. Bohannon RW, Gajdosik RL, LeVeau BF. Isokinetic knee flexion and extension torque in the upright sitting and semireclined sitting positions. *Phys Ther.* 1986;66(7):1083–1086.

24. Lunnen JD, Yack J, LeVeau BF. Relationship between muscle length, muscle activity, and torque of the hamstring muscles. *Phys Ther.* 1981;61(2):190–195.

25. Mohamed O, Perry J, Hislop H. Relationship between wire EMG activity, muscle length, and torque of the hamstrings. *Clin Biomech (Bristol, Avon).* 2002;17(8):569–579.

26. Worrell TW, Perrin DH, Denegar CR. The influence of hip position on quadriceps and hamstring peak torque and reciprocal muscle group ratio values. *J Orthop Sports Phys Ther.* 1989;11(3):104–107.

27. Aagaard P, Simonsen EB, Magnusson SP, Larsson B, Dyhre-Poulsen P. A new concept for isokinetic hamstring: quadriceps muscle strength ratio. *Am J Sports Med.* 1998;26(2):231–237.

28. The SENIAM project. Recommendations for sensor locations on individual muscles. http://www.seniam.org. Accessed February 22, 2012.

29. Hermens HJ, Freriks B, Disselhorst-Klug C, Rau G. Development of recommendations for SEMG sensors and sensor placement procedures. *J Electromyogr Kinesiol.* 2000;10(5):361–374.

30. Gordon AM, Huxley AF, Julian FJ. The variation in isometric tension with sarcomere length in vertebrate muscle fibres. *J Physiol.* 1966;184(1):170–192.

31. Higashihara A, Ono T, Kubota J, Fukubayashi T. Differences in the electromyographic activity of the hamstring muscles during maximal eccentric knee flexion. *Eur J Appl Physiol.* 2010;108(2):355–362.

32. Lynn R, Talbot JA, Morgan DL. Differences in rat skeletal muscles after incline and decline running. *J Appl Physiol.* 1998;85(1):98–104.

33. Blazevich AJ, Cannavan D, Coleman DR, Horne S. Influence of concentric and eccentric resistance training on architectural adaptation in human quadriceps muscles. *J Appl Physiol.* 2007;103(5):1565–1575.

34. Koulouris G, Connell D. Hamstring muscle complex: an imaging review. *Radiographics.* 2005;25(3):571–586.

35. Mendiguchia J, Brughelli M. A return-to-sport algorithm for acute hamstring injuries. *Phys Ther Sport.* 2011;12(1):2–14.

36. Arnason A, Andersen TE, Holme I, Engebretsen L, Bahr R. Prevention of hamstring strains in elite soccer: an intervention study. *Scand J Med Sci Sports.* 2008;18(1):40–48.

37. Gabbe BJ, Branson R, Bennell KL. A pilot randomised controlled trial of eccentric exercise to prevent hamstring injuries in community-level Australian Football. *J Sci Med Sport.* 2006;9(1–2):103–109.

5.4. Article 4

Guex, K., Degache, F., Gremion, G., & Millet, G. P. (2013). Effect of hip flexion angle on hamstring optimum length after a single set of concentric contractions. *Journal of sports sciences, 31*(14), 1545-1552.

Abstract

The eccentric contraction mode was proposed to be the primary stimulus for optimum angle (angle at which peak torque occurs) shift. However, the training range of motion (or muscle excursion range) could be a stimulus as important. The aim of this study was to assess the influence of the training range of motion stimulus on the hamstring optimum length. It was hypothesised that performing a single set of concentric contractions beyond optimal length (seated at 80° of hip flexion) would lead to an immediate shift of the optimum angle to longer muscle length while performing it below (supine at 0° of hip flexion) would not provide any shift. Eleven male participants were assessed on an isokinetic dynamometer. In both positions, the test consisted of 30 consecutive knee flexions at 4.19 rad · s^{-1}. The optimum angle was significantly shifted by ~15° in the direction of longer muscle length after the contractions at 80° of hip flexion, while a non-significant shift of 3° was found at 0°. The hamstring fatigability was not influenced by the hip position. It was concluded that the training range of motion seems to be a relevant stimulus for shifting the optimum angle to longer muscle length. Moreover, fatigue appears as a mechanism partly responsible for the observed shift. ***Keywords:*** optimum angle, eccentric, length-tension relationship, fatigue.

Introduction

In the field of sports activities, one of the most frequent injuries is the hamstring strain (Alonso et al., 2012; Brooks, Fuller, Kemp, & Reddin, 2005a, 2005b; Ekstrand, Hagglund, & Walden, 2011; Elliott, Zarins, Powell, & Kenyon, 2011; Orchard & Seward, 2002; Woods et al., 2004). From an anatomical point of view, this muscle group is mostly bi-articular (except the short head of the biceps femoris) and therefore could be stretched by the hip flexion as well as by the knee extension. This has an influence on its strength production. Indeed, it was shown that, on an isokinetic dynamometer, as hip flexion increased, hamstring peak torque (PT) increased (Guex, Gojanovic, & Millet, 2012). The suggested mechanism was that with a flexed hip, the hamstring passive structures are likely more stretched and then would contribute to a greater extent to their strength production. On the field, sprinting is the main activity responsible for hamstring muscle strain (Agre, 1985; Brooks et al., 2005b; Woods et al., 2004). Terminal swing and early stance phases have both been proposed to be the main periods of susceptibility to hamstring strain (Chumanov, Schache, Heiderscheit, & Thelen, 2012; Orchard, 2012). However, the terminal swing is believed to be the most critical phase due to the repetition of eccentric contractions to decelerate the knee extension, while the hip is flexed at more than 70° and the knee is extending beyond 40° of flexion, putting the hamstrings beyond their optimal length (Chumanov et al., 2012; Chumanov, Heiderscheit, & Thelen, 2007, 2011; Schache, Wrigley, Baker, & Pandy, 2009; Thelen, Chumanov, Best, Swanson, & Heiderscheit, 2005; Thelen, Chumanov, Hoerth, et al., 2005).

Skeletal muscles have an optimum length for producing maximal force (Gordon, Huxley, & Julian, 1966). A decrease in the optimum knee angle – the knee angle at which hamstring peak torque occurs – is proposed as a potential risk factor for hamstring strain (Brockett, Morgan, & Proske, 2004; Proske, Morgan, Brockett, & Percival, 2004). Conversely, it has been proposed that this risk is reduced when the optimum angle is increased by training (Brockett et al., 2004; Proske et al., 2004). Previous studies have reported a shift of the optimum angle in the direction of longer muscle length after 3 to 10 weeks of eccentric resistance training, which has been suggested to be attributed to an increase in serial sarcomeres' number (Blazevich, Cannavan, Coleman, & Horne, 2007; Kilgallon, Donnelly, & Shafat, 2007; Potier, Alexander, & Seynnes, 2009). A shift of the optimum angle in the direction of longer muscle length was also observed directly after a single bout of eccentric exercise (Bowers, Morgan, & Proske, 2004; Brockett, Morgan, & Proske, 2001; Butterfield & Herzog, 2005; Whitehead, Morgan, Gregory, & Proske, 2003). This immediate shift is believed to be the result of an increased series compliance, an early stage in the process leading to delayed-onset muscle soreness, which is largely specific to eccentric-induced damages (Morgan & Proske, 2004). It has been proposed as a simple and reliable indicator of muscle damage, which indicates the number of overstretched sarcomeres (Morgan, 1990; Morgan & Proske, 2004; Whitehead et al., 2003). It seems likely that this acute modification of the length-tension relationship following a single bout of eccentric resistance exercise represents the early stage of the chronic adaptation observed after repeated bouts of eccentric resistance training. In regard to these results, the contraction mode seems to be the primary stimulus for optimum length shift.

The magnitude of the shift was shown to be dependent on the length at which the eccentric contractions are performed. Indeed, a larger shift of the optimum angle in the direction of longer muscle length was observed after 50 eccentric contractions performed on the descending part of the length-tension relationship (beyond optimal length) than when they were performed on the ascending part (below optimal length) (Whitehead et al., 2003). The magnitude of the shift was also shown to be dependent on the length range when the concentric contraction mode was used. In fact, after 200 concentric contractions performed around the optimum length – without overstretch of the musculotendinous complex – no shift in optimum angle was found (Morgan, Gregory, & Proske, 2004). Nonetheless, after 10 weeks of concentric versus eccentric training at long muscle length, a similar increase in fascicle length (which is the mechanism that explains a shift of the optimum angle to longer muscle length) associated with a similar increase in eccentric peak torque was observed between the two groups, while the concentric group increased to a larger extent its concentric peak torque (Blazevich et al., 2007). This result is supportive of the training range of motion (or muscle excursion range) being a stimulus as important as the muscle contraction mode for fascicle length adaptations. One may, then, think that performing a single bout of concentric exercise on the descending part of the muscle length-tension relationship would impose overstretch to the sarcomeres, which would increase series compliance and shift the optimum angle to longer muscle length.

Hamstring injury prevention programmes are mostly based on eccentric training methods or devices with either no hip flexion (e.g. Nordic hamstring exercise) (Mjolsnes, Arnason, Osthagen, Raastad, & Bahr, 2004; Petersen, Thorborg, Nielsen, Budtz-Jorgensen, & Holmich, 2011) or non-specific flexion (e.g. yo-yo flywheel ergometer) (Askling, Karlsson, & Thorstensson, 2003). Moreover, one of the most used hamstring strength devices is the prone hamstring curl, which also places the hip on a non-specific flexion angle. In a study (Chleboun, France, Crill, Braddock, & Howell, 2001) on the impact of different hip and knee angles on the fascicle length of the long head of the biceps femoris, it was shown that, at 0° of hip flexion, the sarcomeres were shortened below optimal length (whatever the knee position), whereas at 90° of hip flexion, they were elongated beyond optimal length. When both hip and knee were flexed at 90°, sarcomeres length was optimal (i.e. maximal overlap). Although, protocols including "classical" eccentric exercises have been shown to increase the optimum length of the hamstrings (Brockett et al., 2001; Kilgallon et al., 2007) with a positive effect on the injury rate (Askling et al., 2003; Petersen et al., 2011), it would be interesting to explore if including a hip flexion angle to these exercises, in order to put the hamstrings beyond optimal length, would have a greater impact on the optimum length and consequently on the injury rate.

In order to advance the fundamental knowledge on hamstring mechanics and to suggest potential clinical applications, the aim of this study was to assess the influence of the training range of motion stimulus as distinct from the contraction mode stimulus. So, the influence on the optimum hamstring length of isokinetic concentric contractions performed below versus beyond optimal length was assessed. It was hypothesised that contractions beyond the optimal length would impose overstretch to the sarcomeres and, then, modify the optimum angle in the direction of longer muscle length while performing it below the optimal length would not modify the muscle length-tension relationship.

Methods

Participants

Eleven male participants volunteered to participate in this study (31.8 ± 5.3 years, 180 ± 5 cm, 76.4 ± 8.4 kg). They were sedentary and performed only recreational physical activity. Participants reporting traumatological disorders or history of hip, knee, or ankle pathology or dysfunction were excluded. The study was conducted according to the Declaration of Helsinki (Harriss & Atkinson, 2011). Ethical approval for the project was obtained from the local committee on human research. Participants signed an informed consent after explanation of the study protocol, data collection procedures and significance of the study objectives.

Experimental design

Isokinetic hamstring muscle strength was measured using an isokinetic dynamometer (Biodex System 2, Biodex Medical Systems, Shirley, New York, USA). The dynamometer was calibrated according to the manufacturer's recommendations and following the instructions for optimal reproducibility. Prior to the testing procedures, the participants performed a 10-min warm-up on a cycling ergometer (60 rpm, 80 watts). They were then placed on the dynamometer, stabilisation straps were positioned across participants' chest, pelvis, and ipsilateral thigh. The lever arm shin-pad was positioned just proximal to the lateral malleolus. The participants were tested on their dominant side, defined as the preferred kicking leg. The hip flexion angle was randomly held at 80° (i.e. seated position) or at 0° (i.e. supine position). The two positions were assessed in two sessions separated by seven days (i.e. one position per session). Each session took place at the same time in the morning, two hours after the last meal. Caffeinated drinks were forbidden. The knee range of motion was 70° (i.e. between 30° and 100° of knee flexion). Hip positions and knee range of motion were chosen to be specific of the sprinting mechanics (Chumanov et al., 2007; Thelen, Chumanov, Hoerth, et al., 2005). Before testing, gravity correction was obtained by measuring the torque exerted on the lever arm shin-pad with the knee in extension in a relaxed state. Measurements started with an initial familiarisation of 10 reciprocal flexion repetitions at 3.14 rad · s^{-1} followed by a 4-min rest period.

The isokinetic test consisted of a set of 30 consecutive knee flexion movements at angular velocities of 4.19 rad · s^{-1} (total duration ~30 s). This number of reciprocal concentric contractions was chosen because it appears to be the better compromise between reliability and physiological interpretability of the data (Bosquet et al., 2010). Moreover, 30 s of duration corresponds to the current recommendation for anaerobic tests (Green, 1995). The fast angular velocity was chosen to be close to the sprinting gesture velocity. Given that hamstring isokinetic peak torque (intraclass correlation coefficient (ICC) = 0.99 at 1.05, 2.09 and 3.14 rad · s^{-1}; coefficient of variation (CV) = 3.1% at 1.05 rad · s^{-1}, 4.2% at 2.09 rad · s^{-1} and 4.1% at 3.14 rad · s^{-1}) and optimum angle of knee flexion (ICC = 0.52 at 1.05 rad · s^{-1}, 0.70 at 2.09 rad · s^{-1} and 0.84 at 3.14 rad · s^{-1}; CV = 11.1% at 1.05 rad · s^{-1}, 10.2% at 2.09 rad · s^{-1} and 11.6% at 3.14 rad · s^{-1}) have both been reported to be reliable at other angular velocities (Maffiuletti, Bizzini, Desbrosses, Babault, & Munzinger, 2007), we assumed that assessment at 4.19 rad · s^{-1} is also reliable. For the extension, the angular speed was fixed at 6.98 rad · s^{-1} to minimise the quadriceps resistance. During the testing procedure participants were asked to fold their arms across their chest. Visual feedback from the Biodex computer monitor was not provided, but they were verbally encouraged to work as hard as possible from the first to the last repetition.

Data analysis

Torque and position data were recorded from the Biodex with a sampling rate of 100 Hz. Raw data were extracted and then analysed with Microsoft Excel 2007 software (Microsoft Corporation, Redmond, WA, USA). Peak torque of each repetition at 0° and 80° of hip flexion were computed for each participant. The highest value in the 30 repetitions was considered as the maximal peak torque ($PTmax_0$ and $PTmax_{80}$), while the lowest was considered as the minimum peak torque ($PTmin_0$ and $PTmin_{80}$). The optimum angles of knee flexion for $PTmax_{80}$, $PTmin_{80}$, $PTmax_0$ and $PTmin_0$ were computed. Relative peak torque of each repetition was calculated with the following formula:

$$\text{Relative PT} = \text{PT} \cdot 100 \ / \ \text{PTmax}$$

Muscular fatigability was monitored in order to test the amount of force reduction in both hip positions. Here, fatigue has been defined as any reduction in the force generating capacity of the total neuromuscular system (Bigland-Ritchie & Woods, 1984). The data of the first contraction of each series were removed from the analyses. Three indexes were calculated: first, the fatigue index (FI) (Kannus, 1994):

$$\text{FI} = 100 - [(\text{average PT of repetitions 28 to 30} \ / \ \text{average PT of repetitions 2 to 4}) \cdot 100]$$

Second, the percentage decrease in performance (DP) (Glaister, Stone, Stewart, Hughes, & Moir, 2004):

$$\text{DP} = 100 - [(\Sigma \text{ PT of repetitions 2 to 30} \ / \ \text{PTmax} \cdot 29) \cdot 100$$

Finally, absolute and relative slopes were determined via linear regression analysis by plotting absolute and relative peak torques of each repetition except the first one. The slope from the calculated regression equation (β-values) for each participant was then obtained to quantify the rate of decrease in absolute and relative peak torques over the last 29 contractions (Maffiuletti et al., 2007; Pincivero, Gear, & Sterner, 2001).

Statistical analysis

Mean and standard deviation (s) values were calculated for all variables. Normal distribution of the data was verified by the Shapiro-Wilk normality test. Paired t-tests were used to compare absolute and relative peak torques of each repetition and the different indexes of muscle fatigue between 0° and 80° of hip flexion. Two-way (hip flexion angle [0°, 80°] by repetition [PTmax, PTmin]) analysis of variance (ANOVA) with repeated measures were used to analyse peak torques and optimum angles. Tukey post-hoc tests were used to localise the differences between means. Significance was set at $P < 0.05$. Statistical analysis was performed with SigmaPlot 11.0 (Systat Software Inc., San Jose, CA).

Results

Results for peak torques and optimum knee angles are presented in Table I. In both positions of hip flexion, PTmax was achieved during the first three repetitions (2.4 ± 1.0 and 2.7 ± 1.7 at 80° and 0°, respectively) and PTmin during the last two (29.0 ± 1.6 and 29.6 ± 0.8 at 80° and 0°, respectively), confirming the presence of an increasing fatigue throughout the protocol for all participants and, then, a good execution of the fatigue test.

Table I. Changes in peak torques and optimum knee angles at 80° and 0° of hip flexion between maximal and minimum peak torques repetitions (mean ± *s*).

Variable	Hip flexion	PTmax	PTmin	PTmax-min % change	Effect size
Peak torque [N · m]	0°	50.1 ± 7.4	28.6 ± 5.6***	-42.7 ± 10.3	3.44 (very large)
	80°	79.4 ± 12.7†††	43.1 ± 7.5*** †††	-45.4 ± 7.7	3.65 (very large)
Optimum knee angle [°]	0°	58.6 ± 14.2	55.6 ± 10.1		0.26 (small)
	80°	88.5 ± 8.5†††	73.3 ± 16.6** †		1.21 (very large)

Abbreviations: PTmax, maximal peak torque; PTmin, minimum peak torque; ** $P < 0.01$, *** $P < 0.001$ for differences with PTmax; † $P < 0.05$, ††† $P < 0.001$ for differences with 0° of hip flexion.

Optimum angle

The optimum angle of knee flexion was higher (P = 0.003) in $PTmax_{80}$ than in $PTmin_{80}$ (Figure 1, A), while no significant difference was found (P = 0.557) between $PTmax_0$ and $PTmin_0$ (Figure 1, B). The shift of the optimum angle was higher (15.2° vs. 3.0°, P = 0.015) for a hip angle of 80° than 0°. The optimum angles were higher (P < 0.05) in $PTmax_{80}$ and $PTmin_{80}$ than in $PTmax_0$ and $PTmin_0$, respectively.

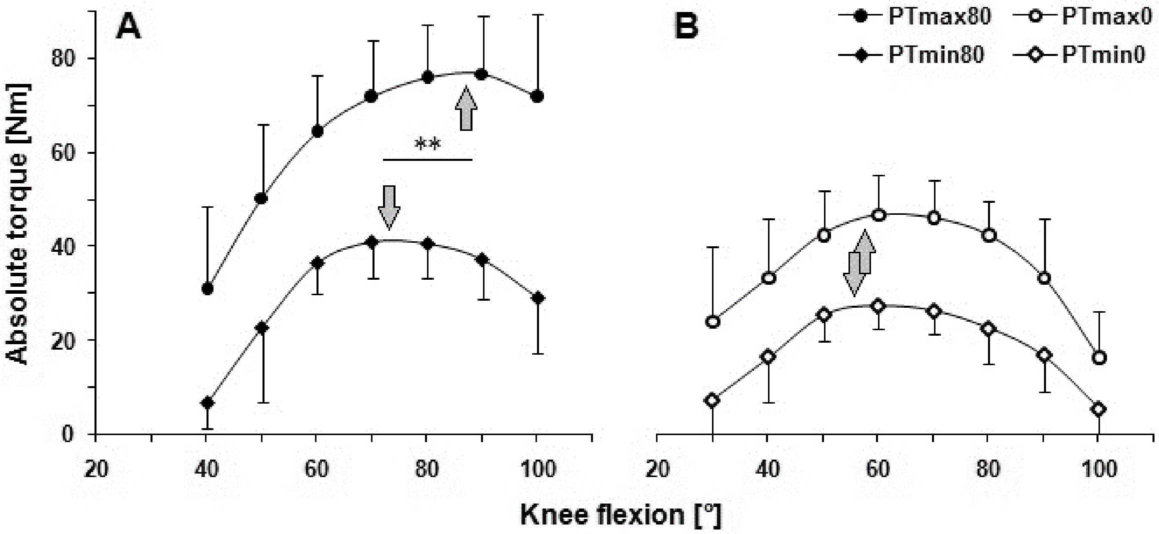


Figure 1. Length-tension relationship for maximal and minimum peak torque repetitions at 80° (A) and 0° (B) of hip flexion. The optimum angles are localised by the grey arrows. ** P < 0.01, for difference between optimum angle for $PTmax_{80}$ and $PTmin_{80}$.

Peak torque

At each repetition, absolute peak torque at 80° of hip flexion was higher ($P < 0.01$) than at 0° (Figure 2, A). However, relative peak torque at each repetition was not different between 80° and 0° (Figure 2, B). At both hip angles, peak torques were lower ($P < 0.001$) in PTmin than in PTmax.

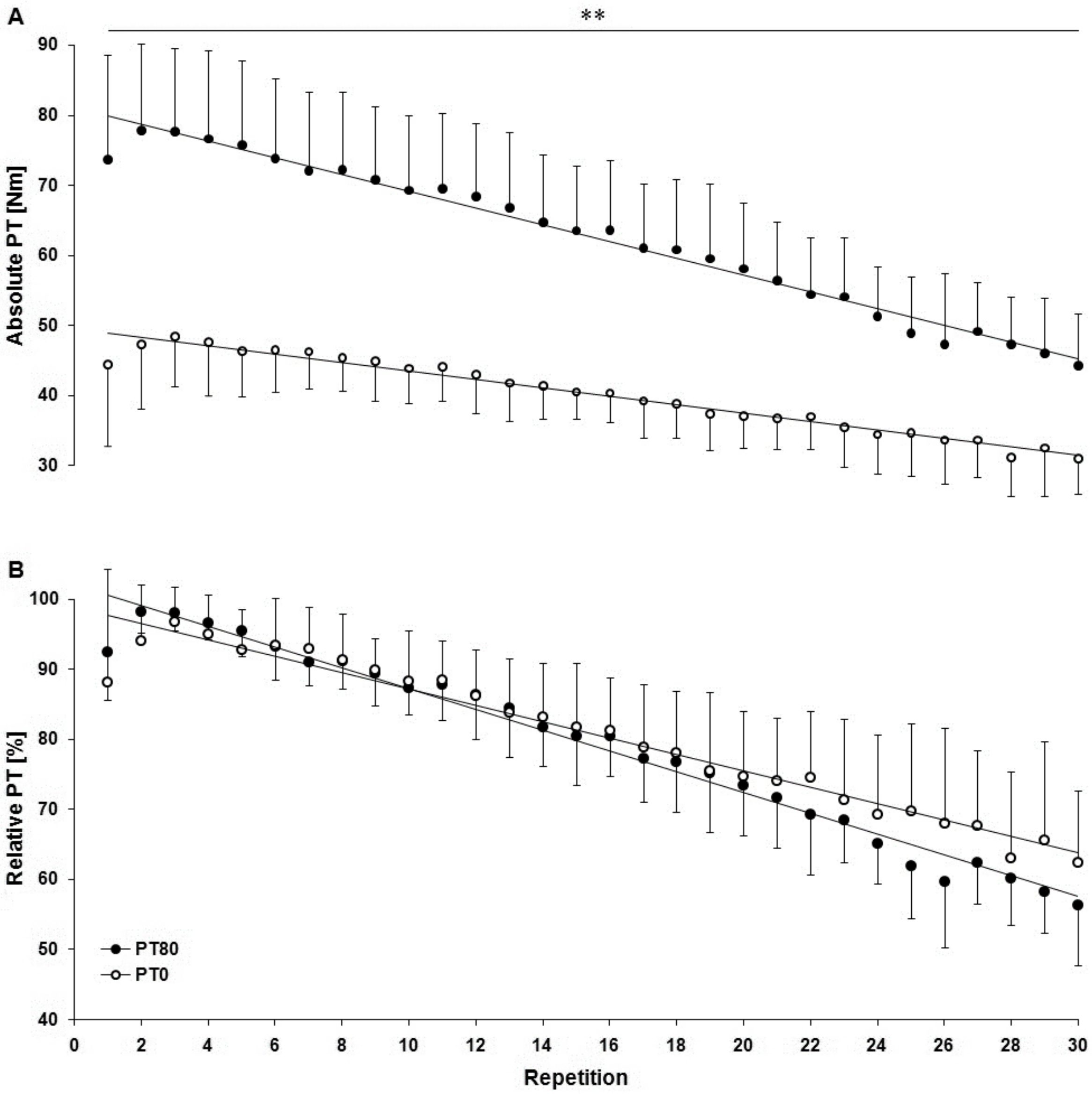


Figure 2. Absolute (A) and relative (B) peak torques for the 30 repetitions at 80° and 0° of hip flexion. ** $P < 0.01$, for differences between absolute peak torques at 80° and 0° of hip flexion.

Fatigue indexes

Results for indexes of knee flexor muscle fatigue are presented in Table II. Absolute slope was higher (P < 0.001) at 80° of hip flexion than at 0° (Figure 1, A). However, fatigue index, percentage decrease in performance and relative slope were not different (P = 0.177, P = 0.464, P = 0.093, respectively) between 80° and 0° of hip flexion (Figure 1, B), confirming that the anaerobic set induced the same amount of force reduction in both hip positions.

Table II. Indexes of muscle fatigue at 80° and 0° of hip flexion (mean ± *s*). The set of 30 concentric contractions produced the same amount of reduction in the force in both hip positions.

Variable	Hip flexion	
	80°	0°
FI [%]	40.2 ± 7.7	32.8 ± 15.0
DP [%]	21.5 ± 4.2	19.6 ± 7.1
Absolute slope [N · m · rep^{-1}]	-1.23 ± 0.40	-0.63 ± 0.29***
Relative slope [N · m · rep^{-1}]	-1.54 ± 0.35	-1.24 ± 0.49

Abbreviations: FI, fatigue index; DP, percentage decrease in performance; *** P < 0.001 for difference with 80° of hip flexion.

Discussion

The aim of this study was to examine the influence on the optimum knee angle of a local concentric anaerobic activity of the hamstrings performed in two different positions: seated, in order to place the hamstrings on the descending part of the muscle length-tension curve, versus supine, in order to place the hamstrings on the ascending part of the muscle length-tension curve. In line with our hypothesis, between the highest and the lowest peak torques of the 30 concentric contractions at 80° of hip flexion, an average shift of 15.2° of the optimum knee angle (from 88.5 ± 8.5° to 73.3 ± 16.6°) was observed (Figure 2, A), while, at 0° of hip flexion the optimum angle was not significantly shifted (58.6 ± 14.2° vs. 55.6 ± 10.1°) (Figure 2, B). Directly after an eccentric exercise, a shift of optimum length has been proposed as a reliable indicator of muscle damage (Morgan, 1990). Here, the participants performed only concentric contractions, which are known to be damage-free if they are performed without overstretch of the musculotendinous complex (Morgan et al., 2004). However, as shown by Blazevich et al. (2007), after 10 weeks of training, if concentric contraction is performed at long muscle length, it leads to a similar increase in fascicle length than after eccentric training. This result is supportive of the training range of motion being a stimulus as important as the contraction mode for fascicle length adaptation. The shift observed in the present study is even higher than those found after a single bout of eccentric exercise performed below optimal length. Indeed, a shift of 7.7° was observed after 12 sets of 6 repetitions of Nordic hamstring exercise (Brockett et al., 2001), and a shift of 7° was found after 5 sets of 10 eccentric contractions of the dorsiflexors (Butterfield & Herzog, 2005). However, when the eccentric exercise was performed beyond optimal length (240 repetitions of stepping down from a box), a shift of 15.4° in the knee extensors was observed (Bowers et al., 2004). Taken together, our results suggest that, as proposed by Blazevich et al. (2007), the training range of motion seems to be an important stimulus for increasing the series compliance and, then, shifting the optimum angle to longer muscle length. However, as the present study did not compare the training range of motion along with the mode of contraction, it is difficult to estimate if the training range of motion is a stimulus as important as the eccentric contraction mode for increasing the series compliance.

As stated in the introduction, if this acute shift of the optimum angle following a single bout of eccentric resistance exercise represents the early stage of the chronic adaptation observed after repeated bouts of eccentric resistance training, one may hypothesise that after repeated bouts of concentric resistance training at long musculotendinous length an increase in fascicle length would be found. In fact, this was already demonstrated by Blazevich et al. (2007) who found a 6% increase in fascicle length of the vastus lateralis after 10 weeks of concentric training at long muscle length.

The maximal peak torque value was found when the participants were seated at 80° of hip flexion and had their knee flexed at 88.5°. This is in line with the findings of Chleboun et al. (2001), who showed that sarcomeres' length was optimal (i.e. maximal overlap) when hip and knee were flexed at 90°. In the supine position, optimum knee angle was found in a less flexed position than in the seated position (58.6 ± 14.2° vs. 88.5 ± 8.5°, $P < 0.001$) in order to place the sarcomeres in better overlap position (Gordon et al., 1966).

No significant difference in the amount of fatigue was found after 30 concentric contractions performed at 0° versus at 80° of hip flexion although, as previously demonstrated (Guex et al., 2012), PTmax was higher when the hip was flexed. Due to the bi-articular nature of the hamstrings, passive structures are more stretched when the hip is flexed. Then, in this position, they would contribute to a greater extent to the hamstring strength production. However, the magnitude of the stretch seems to have no influence on the knee flexors' fatigability. After the 30 contractions performed at 0° of hip flexion, a non-significant shift of 3° was found. Butterfield and Herzog (2005) showed a similar amount of shift (3°) after 5 sets of 10 isometric contractions of the dorsiflexors at optimal length, which represents an important part (~40%) of the whole shift of 7° induced by 5 sets of 10 eccentric contractions. These authors argued that the shift in optimum angle is due to the combination of increased series compliance of the muscle and of fatigue. The shift is, therefore, not an exclusive indicator of muscle damage. In our study, we can estimate that, at 80° of hip flexion, ~20% (3°) of the total shift (15.2°) was due to the exercise-induced fatigue and ~80% to the stretch level and therefore the range of motion.

Our results have some implications in the field of injury prevention since the descending part of the torque-length curve is thought to be a vulnerable region for hamstring injuries (Brughelli & Cronin, 2008). The terminal swing phase of the running cycle places the sarcomeres of the bi-articular hamstrings in the descending portion of the torque-length curve. One may hypothesise that performing hamstring strengthening exercises at a long musculotendinous length with a high hip angle may be more efficient to prevent injury in sports requiring high-speed running by inducing a shift of the optimum angle to a longer muscle length. Some authors (Brughelli & Cronin, 2008; Malliaropoulos et al., 2012; Oliver & Dougherty, 2009) have proposed relevant exercises that include hip flexion (e.g. eccentric stiff-leg deadlift, eccentric single leg deadlifts, hamstring catapult, sprinter eccentric leg curl, eccentric loaded lunge drops, barbell leg curl, eccentric box drop, razor curl). This type of exercise could be even more efficient than strengthening with a lower (or without) hip flexion as in most of the current "classical" eccentric hamstring exercises like the Nordic hamstring exercise or the lying hamstring curl. However, this remains to be proven in future studies. Inclusion of concentric contraction might be possible as long this long musculotendinous length is respected (i.e. the hip angle is high).

This study has some limitations. First, it would have been interesting to explore the effect on optimum angle of 30 eccentric contractions in the two different hip flexion positions and to compare with the present results. Hamstrings have not often the occasion to produce repetitive maximal concentric contractions in many sports since their function consists most of the time in decelerating the lower leg during knee extension. However, the delayed-onset muscle soreness resulting from repetitive eccentric contractions would be so high that it was chosen not to test it. Second, muscle damage interpretation was only based on the observed shift in optimum length. Delayed-onset muscle soreness monitoring, blood analysis and/or imagery would have been relevant methods to support our hypotheses. Third, the reliability of the data was not tested in this study. Finally, the present study assessed only the optimum length of the hamstrings. Therefore, the efficiency of concentric contractions performed at long muscle length to prevent hamstring strains remains to be proven; this could be the aim of future research.

Conclusion

In summary, the present study showed that: 1) hamstring optimal length was shifted significantly by 15.2° in the direction of longer muscle length after 30 concentric contractions performed on the descending part of the muscle length-tension curve (i.e. with a hip angle of 80°) but only non-significantly by 3° when performed on the ascending part (i.e. with a hip angle of 0°); 2) Hip flexion angle did not influence the amount of fatigue of the hamstrings during 30 consecutive concentric contractions; and 3) Hamstring peak torques were always higher at 80° than at 0° throughout the 30 contractions.

We conclude that the training range of motion could be an important stimulus for increasing the series compliance, leading to an immediate shift of the muscle length-tension relationship. Moreover, fatigue appears as a mechanism partly responsible for the observed shift in optimum knee angle.

References

Agre, J. C. (1985). Hamstring injuries. Proposed aetiological factors, prevention, and treatment. *Sports Medicine, 2*(1), 21–33.

Alonso, J. M., Edouard, P., Fischetto, G., Adams, B., Depiesse, F., & Mountjoy, M. (2012). Determination of future prevention strategies in elite track and field: Analysis of Daegu 2011 IAAF Championships injuries and illnesses surveillance. *British Journal of Sports Medicine, 46*(7), 505–514.

Askling, C., Karlsson, J., & Thorstensson, A. (2003). Hamstring injury occurrence in elite soccer players after preseason strength training with eccentric overload. *Scandinavian Journal of Medicine and Science in Sports, 13*(4), 244–250.

Bigland-Ritchie, B., & Woods, J. J. (1984). Changes in muscle contractile properties and neural control during human muscular fatigue. *Muscle and Nerve, 7*(9), 691–699.

Blazevich, A. J., Cannavan, D., Coleman, D. R., & Horne, S. (2007). Influence of concentric and eccentric resistance training on architectural adaptation in human quadriceps muscles. *Journal of Applied Physiology, 103*(5), 1565–1575.

Bosquet, L., Maquet, D., Forthomme, B., Nowak, N., Lehance, C., & Croisier, J. L. (2010). Effect of the lengthening of the protocol on the reliability of muscle fatigue indicators. *International Journal of Sports Medicine, 31*(2), 82–88.

Bowers, E. J., Morgan, D. L., & Proske, U. (2004). Damage to the human quadriceps muscle from eccentric exercise and the training effect. *Journal of Sports Sciences, 22*(11–12), 1005–1014.

Brockett, C. L., Morgan, D. L., & Proske, U. (2001). Human hamstring muscles adapt to eccentric exercise by changing optimum length. *Medicine and Science in Sports and Exercise, 33*(5), 783–790.

Brockett, C. L., Morgan, D. L., & Proske, U. (2004). Predicting hamstring strain injury in elite athletes. *Medicine and Science in Sports and Exercise, 36*(3), 379–387.

Brooks, J. H., Fuller, C. W., Kemp, S. P., & Reddin, D. B. (2005a). Epidemiology of injuries in English professional rugby union: Part 1 match injuries. *British Journal of Sports Medicine, 39*(10), 757–766.

Brooks, J. H., Fuller, C. W., Kemp, S. P., & Reddin, D. B. (2005b). Epidemiology of injuries in English professional rugby union: Part 2 training injuries. *British Journal of Sports Medicine, 39*(10), 767–775.

Brughelli, M., & Cronin, J. (2008). Preventing hamstring injuries in sport. *Strength and Conditioning Journal, 30*(1), 55–64.

Butterfield, T. A., & Herzog, W. (2005). Is the force-length relationship a useful indicator of contractile element damage following eccentric exercise? *Journal of Biomechanics, 38*(9), 1932–1937.

Chleboun, G. S., France, A. R., Crill, M. T., Braddock, H. K., & Howell, J. N. (2001). In vivo measurement of fascicle length and pennation angle of the human biceps femoris muscle. *Cells, Tissues, Organs, 169*(4), 401–409.

Chumanov, E. S., Heiderscheit, B. C., & Thelen, D. G. (2007). The effect of speed and influence of individual muscles on hamstring mechanics during the swing phase of sprinting. *Journal of Biomechanics, 40*(16), 3555–3562.

Chumanov, E. S., Heiderscheit, B. C., & Thelen, D. G. (2011). Hamstring musculotendon dynamics during stance and swing phases of high-speed running. *Medicine and Science in Sports and Exercise, 43*(3), 525–532.

Chumanov, E. S., Schache, A. G., Heiderscheit, B. C., & Thelen, D. G. (2012). Hamstrings are most susceptible to injury during the late swing phase of sprinting. *British Journal of Sports Medicine, 46*(2), 90.

Ekstrand, J., Hagglund, M., & Walden, M. (2011). Injury incidence and injury patterns in professional football: The UEFA injury study. *British Journal of Sports Medicine, 45*(7), 553–558.

Elliott, M. C., Zarins, B., Powell, J. W., & Kenyon, C. D. (2011). Hamstring muscle strains in professional football players: A 10-year review. *The American Journal of Sports Medicine, 39*(4), 843–850.

Glaister, M., Stone, M. H., Stewart, A. M., Hughes, M., & Moir, G. L. (2004). The reliability and validity of fatigue measures during short-duration maximal-intensity intermittent cycling. *Journal of Strength and Conditioning Research / National Strength and Conditioning Association, 18*(3), 459–462.

Gordon, A. M., Huxley, A. F., & Julian, F. J. (1966). The variation in isometric tension with sarcomere length in vertebrate muscle fibres. *The Journal of Physiology, 184*(1), 170–192.

Green, S. (1995). Measurement of anaerobic work capacities in humans. *Sports Medicine, 19*(1), 32–42.

Guex, K., Gojanovic, B., & Millet, G. P. (2012). Influence of hip-flexion angle on hamstrings isokinetic activity in sprinters. *Journal of Athletic Training, 47*(4), 390–395.

Harriss, D. J., & Atkinson, G. (2011). Update–Ethical standards in sport and exercise science research. *International Journal of Sports Medicine, 32*(11), 819–821.

Kannus, P. (1994). Isokinetic evaluation of muscular performance: Implications for muscle testing and rehabilitation. *International Journal of Sports Medicine, 15* (Suppl. 1), S11–18.

Kilgallon, M., Donnelly, A. E., & Shafat, A. (2007). Progressive resistance training temporarily alters hamstring torque-angle relationship. *Scandinavian Journal of Medicine and Science in Sports, 17*(1), 18–24.

Maffiuletti, N. A., Bizzini, M., Desbrosses, K., Babault, N., & Munzinger, U. (2007). Reliability of knee extension and flexion measurements using the Con-Trex isokinetic dynamometer. *Clinical Physiology and Functional Imaging, 27*(6), 346–353.

Malliaropoulos, N., Mendiguchia, J., Pehlivanidis, H., Papadopoulou, S., Valle, X., Malliaras, P., & Maffulli, N. (2012). Hamstring exercises for track and field athletes: Injury and exercise biomechanics, and possible implications for exercise selection and primary prevention. *British Journal of Sports Medicine, 46*(12), 846–851.

Mjolsnes, R., Arnason, A., Osthagen, T., Raastad, T., & Bahr, R. (2004). A 10-week randomized trial comparing eccentric vs. concentric hamstring strength training in well-trained soccer players. *Scandinavian Journal of Medicine and Science in Sports, 14*(5), 311–317.

Morgan, D. L. (1990). New insights into the behavior of muscle during active lengthening. *Biophysical Journal, 57*(2), 209–221.

Morgan, D. L., Gregory, J. E., & Proske, U. (2004). The influence of fatigue on damage from eccentric contractions in the gastrocnemius muscle of the cat. *The Journal of Physiology, 561* (Pt 3), 841–850.

Morgan, D. L., & Proske, U. (2004). Popping sarcomere hypothesis explains stretch-induced muscle damage. *Clinical and Experimental Pharmacology and Physiology, 31*(8), 541–545.

Oliver, G. D., & Dougherty, C. P. (2009). The razor curl: A functional approach to hamstring training. *Journal of Strength and Conditioning Research / National Strength and Conditioning Association, 23*(2), 401–405.

Orchard, J., & Seward, H. (2002). Epidemiology of injuries in the Australian Football League, seasons 1997-2000. *British Journal of Sports Medicine, 36*(1), 39–44.

Orchard, J. W. (2012). Hamstrings are most susceptible to injury during the early stance phase of sprinting. *British Journal of Sports Medicine, 46*(2), 88–89.

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

Pincivero, D. M., Gear, W. S., & Sterner, R. L. (2001). Assessment of the reliability of high-intensity quadriceps femoris muscle fatigue. *Medicine and Science in Sports and Exercise, 33*(2), 334–338.

Potier, T. G., Alexander, C. M., & Seynnes, O. R. (2009). Effects of eccentric strength training on biceps femoris muscle architecture and knee joint range of movement. *European Journal of Applied Physiology, 105*(6), 939–944.

Proske, U., Morgan, D. L., Brockett, C. L., & Percival, P. (2004). Identifying athletes at risk of hamstring strains and how to protect them. *Clinical and Experimental Pharmacology and Physiology, 31*(8), 546–550.

Schache, A. G., Wrigley, T. V., Baker, R., & Pandy, M. G. (2009). Biomechanical response to hamstring muscle strain injury. *Gait and Posture, 29*(2), 332–338.

Thelen, D. G., Chumanov, E. S., Best, T. M., Swanson, S. C., & Heiderscheit, B. C. (2005). Simulation of biceps femoris musculotendon mechanics during the swing phase of sprinting. *Medicine and Science in Sports and Exercise, 37*(11), 1931–1938.

Thelen, D. G., Chumanov, E. S., Hoerth, D. M., Best, T. M., Swanson, S. C., Li, L. , .Heiderscheit, B. C. (2005). Hamstring muscle kinematics during treadmill sprinting. *Medicine and Science in Sports and Exercise, 37*(1), 108–114.

Whitehead, N. P., Morgan, D. L., Gregory, J. E., & Proske, U. (2003). Rises in whole muscle passive tension of mammalian muscle after eccentric contractions at different lengths. *Journal of Applied Physiology, 95*(3), 1224–1234.

Woods, C., Hawkins, R. D., Maltby, S., Hulse, M., Thomas, A., Hodson, A., & Football Association Medical Research Programme. (2004). The Football Association Medical Research Programme: An audit of injuries in professional football–analysis of hamstring injuries. *British Journal of Sports Medicine, 38*(1), 36–41.

5.5. Article 5

Guex, K., & Millet, G. P. (2013). Conceptual framework for strengthening exercises to prevent hamstring strains. *Sports medicine, 43*(12), 1207-1215.

Abstract

High-speed running accounts for the majority of hamstring strains in many sports. The terminal swing phase is believed to be the most hazardous as the hamstrings are undergoing an active lengthening contraction in a long muscle length position. Prevention-based strength training mainly focuses on eccentric exercises. However, it appears crucial to integrate other parameters than the contraction type. Therefore, the aim of this study is to present a conceptual framework based on six key parameters (contraction type, load, range of motion, angular velocity, uni-/bilateral exercises, kinetic chain) for the hamstring's strength exercise for strain prevention. Based on the biomechanical parameters of sprinting, it is proposed to use high-load eccentric contractions. The movement should be performed at a slow to moderate angular velocity and focused at the knee joint, while the hip is kept in a large flexion position in order to reach a greater elongation stress of the hamstrings than in the terminal swing phase. In this way, we believe that, during sprinting, athletes would be better trained to brake the knee extension effectively in the whole range of motion without overstretch of the hamstrings. Finally, based on its functional application, unilateral open kinetic chain should be preferred.

Acknowledgments

The authors would like to thank Mrs. Weibel-Pache for her contribution during the preparation of this manuscript. No funding was used to assist in the preparation of this article. The authors have no conflicts of interest that are directly relevant to the content of this article.

1 Introduction

Hamstring strain injuries have a high prevalence in many sports, including soccer [1, 2], rugby [3, 4], Australian football [5], American football [6], Gaelic football [7], and sprinting [8–11]. High-speed running—the common point between these activities—accounts for the majority of hamstring strains [2, 7, 12, 13]. A good understanding of the biomechanical characteristics responsible for this injury during running is required to optimize the preventive intervention.

The running cycle begins when one foot comes in contact with the ground (0 %) and ends when the same foot contacts the ground again (100 %). It is split into two separate phases: the stance and the swing. Toe off marks the end of stance and the beginning of the swing phase. It occurs at ~39 % of the running cycle when running [14] and at ~22 % when sprinting [15]. Terminal swing and early stance phases have both been proposed to be the main periods for hamstring strain [16, 17]. However, the terminal swing is believed to be the most hazardous for many reasons [2, 18–23]. First, between 75 and 85 % of the running cycle, the hamstrings are undergoing an active lengthening contraction (i.e., eccentric) [19]. The repetition of eccentric contractions, as is the case during sprinting, has the potential to induce damage within the muscle [24, 25]. Furthermore, the musculotendon peak force is reached at ~85 % of the running cycle and it was shown that the loads during the terminal swings exceed those during stance [19]. Second, during this phase, the combination of hip flexion and knee extension induces a substantial elongation stress on the biarticular hamstrings (Fig. 1) [19]. At ~85 % of the running cycle, the semimembranosus, semitendinosus, and long head of the biceps femoris are stretched by 9.8, 8.7, and 12.0 %, respectively, beyond their upright lengths (i.e., hip and knee at 0° of flexion) [19]. Due to the stretch-shortening cycle – the transition between negative and positive power takes place at ~85 % of the running cycle [19] – the local elongation stress on the myotendinous junctions and tendons (i.e., the most sensitive structures to strain [26, 27]) is increased. Finally, two case studies have reported biomechanical data when running athletes incurred acute hamstring strain injuries [20, 21]. Both studies described the terminal swing rather than stance as the most likely time of injury.

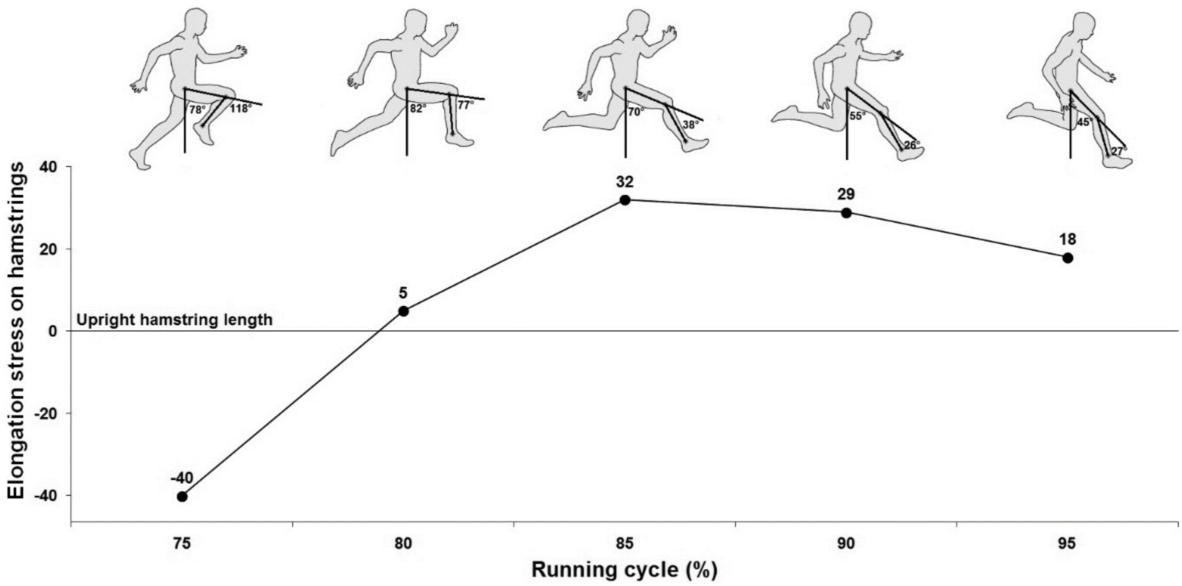


Fig. 1 Terminal swing phase of the right leg of a world-class sprinter, corresponding to 75, 80, 85, 90, and 95 % of the running cycle. At ~85 %, the hamstrings reach their elongation peak. The "elongation stress" on hamstrings is determined by subtracting the knee angle from the hip angle. The left leg is in the early swing phase, corresponding to 25 % (i.e., ~toe off), 30, 35, 40, and 45 % of the running cycle.

Unmodifiable risk factors for hamstring strain injuries, such as age, ethnic origin, and past history of posterior thigh injury have been described [28]. On the other hand, strength imbalances of the hamstrings, such as a weakness [29–31], bilateral asymmetry [32], lower hamstrings to quadriceps ratio [33], and a decrease in the optimum length [34–36], have been suggested as modifiable risk factors of hamstring strain injuries. In order to address these modifiable risk factors, six intervention studies have documented the effects of eccentric exercises on hamstring strain prevention in soccer, rugby, and Australian football [12, 35, 37–40]. Five of the studies used the Nordic hamstring exercise (NHE), while one used the yo-yo hamstring curl exercise [38]. The six studies reported 60–70 % reduction in injury rate compared to control groups after the eccentric exercise protocol. This could be explained by the improvement that was observed after this type of exercise of some of the risk factors such as strength [41–43], the hamstrings to quadriceps ratio [42], or the optimum length [43–45].

Although the reduction in the injury rate observed in these studies is meaningful, a substantial number of hamstring strains still occur. In regard to the stress on the hamstrings during the late swing phase of sprinting, it appears crucial to integrate parameters other than the contraction type (i.e., eccentric) for the conception of strength exercises. Particularly, the load, range of motion, and angular velocity are of great importance. The fact that exercises are uni- versus bilateral and in open versus closed kinetic chain should, in our opinion, also be taken into account. The aim of this study is, therefore, to present a conceptual framework for strengthening exercises to prevent hamstring strains, focusing on six key parameters: (1) contraction type; (2) load; (3) range of motion; (4) angular velocity; (5) uni-/bilateral exercises; and (6) kinetic chain.

2 Contraction type

Contraction type is the most commonly monitored parameter in strength training to prevent hamstring strains. Since the NHE was described in 2001 [44], all researchers [12, 35, 37–40] in the field of hamstring strain prevention have used eccentric exercises, with encouraging results as stated above. The improvement of many risk factors could explain the decrease in injury rate. First, the NHE was shown to be effective in improving the eccentric hamstrings strength [41–43, 46]. Consequently, after 10 weeks of NHE, the ratio between eccentric hamstrings torque and concentric quadriceps torque (mixed H/Q ratio) was shown to be increased from 0.89 to 0.98 [42], which corresponds to the strength status of the normalized muscle [33]. Given that strength training is largely mode specific [42, 47, 48], and that the strains mainly occur when the hamstrings act eccentrically to brake the knee extension at the end of the running swing phase [16], it seems relevant to prioritize this contraction mode to increase the special strength of the hamstrings. Second, the hamstrings' optimum length – the knee angle at which hamstrings' peak torque occurs (Fig. 2) – was found to be shifted in the direction of longer muscle length directly after a single bout of eccentric strength training [44]. Many studies have also observed a shift in the same direction after 3–8 weeks of hamstrings eccentric strength training [41, 43, 45, 49]. However, one study [46] with a high variability in results did not report this shift.

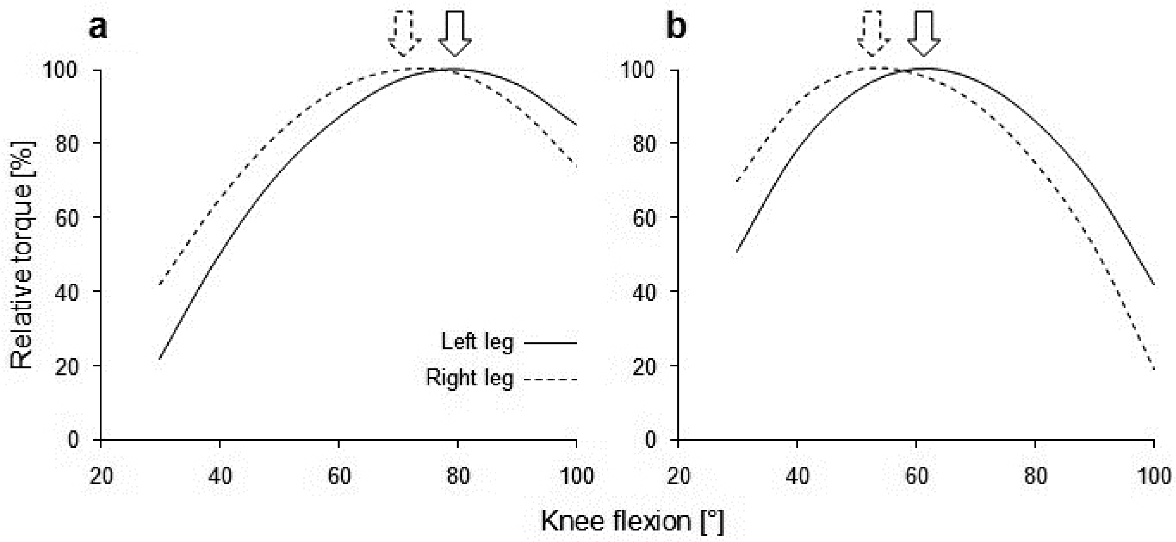


Fig. 2 Example of an unpublished hamstrings' force–length relationship of a national-level sprinter. The arrows represent the optimum length (i.e., knee angle at which hamstrings' peak torque occurs). The test was performed on an isokinetic device at **a** 80° and **b** 0° of hip flexion. In both positions, the hamstrings of the left leg have a lower optimum length than the right leg. The risk of injury is, then, higher for the left hamstring than for the right.

The shift of the optimum length was found to be similar after an acute and a chronic intervention, although the mechanisms are different. After a single bout of eccentric exercise, this shift was believed to be the result of muscle fibers damage, an early stage in the process leading to delayed-onset muscle soreness (DOMS), which is largely specific to eccentric contraction type [50–52]. The disrupted sarcomeres increase the muscle's series compliance (i.e., less force is required to elongate the muscle), leading to a shift in optimum length. After a chronic intervention, the observed shift was attributed to an increase in fascicle length that suggests an addition of sarcomeres in series within the muscle [41, 53, 54]. This allows the muscle to produce its peak force in a longer position without having an overstretch of the sarcomeres. To prevent injury, this chronic adaptation seems particularly relevant regarding the substantial elongation stress on the biarticular hamstrings during the terminal swing phase of the running cycle [19].

3 Load

The hamstrings' weakness has been suggested as a modifiable risk factor of strain injury [29–31] and it was stated that stronger muscles would provide greater protection against strain injury [55]. Muscular strength development involves the coordinated functioning of several processes [56], with the ability to produce maximal force attributed to both neural and muscular components [57]. In the early phases of resistance training, the increases in strength are mainly associated with neural adaptations [56, 57], while hypertrophic responses contribute to the strength gains in the later phases [58].

The load refers to the amount of weight assigned to an exercise set and is probably the most important variable in resistance training program design [59]. It was shown that a load greater than 80–85 % of 1 repetition maximum (RM) is needed to produce further neural adaptations and strength in experienced lifters [60]. This load range appears to maximally recruit muscle fibers and will specifically increase dynamic 1 RM strength [60]. This is relevant in the field of injury prevention, since it was shown that fully stimulated muscles are able to tolerate greater stress before strain than partially activated muscles [55]. Strength increases have been shown to be greater when using heavy weights for 3–5 RM than with 9–11 and 20–28 RM [61]. Therefore, it is recommended that novice to intermediate individuals train with loads corresponding to 60–70 % of 1 RM, while advanced individuals use loads of 80–100 % of 1 RM to maximize muscular strength [62]. So, to optimize strength exercises in the field of hamstring strain prevention, the load should be monitored and be at 80 % of the 1 RM at least in athletes. However, it is suggested that strength developed eccentrically should be 20–60 % higher than concentrically [63]. Kaminski et al. [64], have reported better improvement (+29 vs. +19 %) in hamstring strength after 6 weeks of training twice a week (2 x 8 repetitions) in eccentric at 100 % than in concentric at 80 % of 1 RM. Therefore, using loads corresponding to 100 % of 1 RM at least seems relevant when the resistance exercise is performed in eccentric. In the case of the NHE, for example, it is difficult to adjust the load. The correct and complete execution of the movement is often too arduous for beginners, while it could become too easy for advanced athletes. However, even if the untrained athletes can only brake the knee extension a few degrees of the range of motion, they still do the eccentric contraction for the rest of the movement [46]. For advanced athletes, the load could be increased by pushing on their back.

4 Range of motion

As mentioned in Sect. 2, eccentric resistance training has been shown to shift the hamstrings' optimum angle in the direction of longer muscle length [41, 43, 44, 49]. However, it was reported that the fascicle length adaptations that explain this shift were strongly influenced by factors other than contraction mode [53]. In fact, Blazevich et al. [53] have reported a similar increase in fascicle length of the vastus lateralis after 10 weeks of concentric versus eccentric training at long muscle length. This supports the idea that the training range of motion (i.e., muscle excursion range during loading) is the dominant stimulus for fascicle length adaptation [53]. In line with this result, a recent study showed that 30 concentric contractions of the hamstrings at a long musculotendinous length (at 80° of hip flexion, in a seated position) immediately induced a significant shift of 15° of the optimum knee angle, while 30 concentric contractions of the hamstrings at a short musculotendinous length (at 0° of hip flexion, in a supine position) did not lead to any shift of the optimum angle [65]. Moreover, during eccentric contractions, the magnitude of the shift was shown to be influenced by the muscle length during contractions. Indeed, a larger shift of the optimum length in the direction to longer muscle length was observed after 50 eccentric contractions performed on the descending part of the length–tension relationship (beyond optimal length) than on the ascending part (below optimal length) [51].

From an anatomical point of view, the hamstrings are mainly biarticular muscles (except the short head of the biceps femoris). Therefore, both hip flexion and knee extension are able to stretch them, which influences their strength production. On an isokinetic dynamometer, it was shown that, as hip flexion increased, hamstrings' peak torque increased [66]. The suggested mechanism was that with a flexed hip, the hamstrings' passive structures are likely more stretched and would contribute to a greater extent to their strength production. During the swing phase of sprinting, these two joints have a large range of motion (Fig. 1).

4.1 Hip position

The hip switches from a position of extension at the end of the stance phase to more than 70° of flexion at ~80 % of the running cycle [67]. The hip is still between 60° and 70° of flexion at 85 % of the running cycle when the hamstrings reach their elongation peak. It is, then, extending gradually up to ~45° of flexion before the following stance phase [14, 67].

4.2 Knee position

During the early swing phase, the knee reaches 130° of flexion at ~55 % of the running cycle [14]. The knee is quickly extending to less than 30° at ~95 % of the running cycle [67]. Between 95 and 100 %, the knee is slightly flexing [14, 67].

4.3 Elongation stress

The combination of hip flexion and knee extension induces a substantial elongation stress on the biarticular hamstrings at the end of the swing phase [19]. We propose to assess the amount of elongation by subtracting the knee flexion angle from the hip flexion angle (Fig. 1). If the result is positive, the hamstrings are stretched beyond their optimal length, while if the result is negative, they are placed below optimal length. Zero corresponds to the upright position (i.e., optimal length). The "elongation stress" values obtained with this method are in line with the observations of Chleboun et al. [68] on the fascicle length of the biceps femoris at different hip and knee angles. However, it does not take into account the greater moment arm of the hamstrings at the hip than at the knee [68, 69]. In fact, changing the hip angle had a larger effect on the long head of the biceps' femoris length than changing the knee angle [68, 69]. One may argue that the "elongation stress" values obtained with our method should be even greater when the hip is flexed to a larger extent during sprinting (i.e., between 70 and 90 % of the running cycle).

One may hypothesize that performing hamstring strengthening exercises at a long musculotendinous length with a high hip angle may be more efficient to prevent injury by inducing a shift of the optimum angle to a longer muscle length. Some authors [70–73] have proposed relevant exercises that include hip flexion (e.g., eccentric stiff-leg deadlift, eccentric single leg deadlifts, hamstring catapult, sprinter eccentric leg curl, eccentric loaded lunge drops, barbell leg curl, eccentric box drop, razor curl, lengthened state eccentric training on cable column). This requires further investigation, but these exercises may be more efficient than strengthening with a lower (or without) hip flexion as in most of the current 'classical' eccentric hamstrings exercises, e.g., the lying hamstring curl or the NHE. During the latter exercise, the "elongation stress" on hamstrings is non-existent: the exercise starts at ~90° of knee flexion and 0° of hip flexion (elongation stress = -90). At the end of the movement, the knee is, in the best case, at 0° and the hip still at 0° (elongation stress = 0). Moreover, only a few athletes are able to perform this exercise with the whole range of motion. Therefore, in our view, the NHE does not provide a sufficient "elongation stress" on hamstrings in regard to the sprinting biomechanics.

5 Angular velocity

Between ~25 and 80 % of the running cycle, the hip is flexing with a peak velocity greater than 700°/s [74]. Between ~55 and 95 % of the running cycle, the knee is extending with a peak angular velocity greater than 1,000°/s [74]. In terms of hamstrings' elongation velocity, the peak (~1 m/s) is reached in the early swing phase at about ~60 % of the running cycle [19, 75]. At this point the elongation stress on the biarticular hamstrings is negative. In fact, the hip and the knee are flexed at ~50° and 130°, respectively [67]. From this moment, the hamstrings begin to contract eccentrically to brake the knee extension [75]. Therefore, their elongation velocity gradually decreases until ~85 % of the running cycle, where the transition between negative and positive velocity takes place [19]. As previously mentioned in Sect. 1, this period of stretch-shortening cycle is thought to be the most hazardous for hamstring strain injuries.

It is very complicated to develop strength exercises that reproduce the knee extension velocity (i.e., >1,000°/s) found during the terminal swing of sprinting. However, it was shown that the training adaptations observed after eccentric training were independent from the velocity of exercise [46, 65, 76, 77]. For example, after 4 weeks of NHE – a low movement velocity exercise – the same gain in peak torque was observed, on an isokinetic device, at 60, 120, and 240°/s [46]. This is a promising finding for hamstring strain prevention. In fact, the adaptations observed after an eccentric strength program performed at slow angular velocity may protect the hamstrings' muscle-tendon complex from the fast elongation occurring during the swing phase of sprinting. So, for optimizing strength exercises in the field of hamstring strain prevention, the exercises should be performed at a slow or moderate angular velocity.

6 Uni-/bilateral exercises

As stated above, at ~85 % of the running cycle, the semimembranosus, semitendinosus, and long head of the biceps femoris are stretched by 9.8, 8.7, and 12.0 %, respectively, beyond their upright lengths [19]. This stretch is even greater due to the contralateral hip extending at the same time, which allows only a slight pelvis oscillation around its average angular position during the running cycle [78], while a posterior tilt would have decreased the hamstring stretch. Bilateral hamstrings strength exercises that include hip flexion (e.g., eccentric stiff-leg deadlift, barbell leg curl, eccentric box drop, razor curl, seated hamstring curl), should, then, be performed carefully because the pelvis could easily be tilted in a posterior position. Using unilateral exercises would ensure only a slight pelvis oscillation and, then, a more specific hamstrings "elongation stress".

Since bilateral asymmetry has been suggested as a modifiable risk factor of hamstring strain injuries [32], it seems relevant to propose exercises that are able to strengthen both legs to same extent. In this context, bilateral exercises could allow one limb to support more load than the other one. Clark et al. [45] have observed an increase in optimum length asymmetry between the dominant and non-dominant legs after 4 weeks of training with the NHE. It was hypothesized that the limb with the higher knee extension optimum angle of the hamstrings may be required to take over control of the movement towards the end of the repetition [45]. However, this hypothesis was refuted by Iga et al. [46], who recorded similar electromyographic activity between the dominant and non-dominant legs, suggesting that both hamstrings were recruited to the same extent during NHE. Overall, in regard to the sprinting biomechanics, a unilateral exercise seems more specific.

7 Kinetic chain

The final key parameter is the type of kinetic chain of the exercise. Two types of kinetic chain have been described: the open and the closed kinetic chain. The open one allows a free motion of the distal segment, while in the closed one, the terminal joint meets considerable external resistance that restrains free motion (i.e., generally, the proximal segment moves relative to the distal segment) [79]. In open kinetic chain exercises, the proportion of shear force may be greater, whereas compression forces are greater in closed kinetic chain exercises [80]. From a neurophysiologic point of view, another distinction exists between these two types of kinetic chain. The open kinetic chain motion generally consists of one muscle group acting on a single joint, whereas the closed kinetic chain motion involves multiple joints and controlled contractions of synergistic and antagonistic muscles [81]. In practice, closed-chain exercises are often thought to be benefic due to their more intimate relationship to functional movements, while open-chain exercises are rated advantageously in therapy and training in isolated arthromuscular queries [81].

When sprinting, the swing phase consists of one open kinetic chain activity where the hamstrings' role is to brake the knee extension up to ~85 % of the running cycle (i.e., at the "elongation stress" peak) [19]. One may, then, argue that performing open-chain kinetic exercises would be more specific to this phase of sprinting, although the influence of this latter parameter remains unclear.

The lying hamstring curl is clearly an open kinetic chain exercise but the NHE is difficult to classify. Some authors [70, 71] consider the NHE to be an open-chain exercise, probably due to the single-joint movement at the knee, whereas it might also be considered to be a closed-chain exercise due to the considerable external resistance that restrains free motion of the distal segment. The same confusion exists for other exercises such as the single leg deadlift. In fact, this exercise is described as a closed-chain exercise [70], while it might also be considered an open-chain exercise due to the single-joint movement at the hip.

8 Conclusion

In our view, hamstring strength exercises should be more specific to the terminal swing phase of sprinting. Based on the biomechanical parameters of sprinting, we therefore propose a conceptual framework for analyzing the current exercises and designing new ones (Table 1). It is proposed that the focus should be on high-load eccentric contractions at the knee joint and to keep the hip in a large flexion position (80°) in order to reach a greater "elongation stress" than in the terminal swing. In this way, we believe that, during sprinting, athletes would be better trained to brake the knee extension effectively in the whole range of motion without overstretch of the hamstrings. In Table 2, some of the hamstring strength exercises most frequently used currently are analyzed. This article suggests clearly that the 'optimal' exercise has not been designed yet. Therefore, further investigations on hamstring strain prevention should focus on this point.

Table 1 Proposal for a new framework for hamstring strain preventive exercises.

Parameters	Start position	Range of motion	End position
Contraction type	Eccentric		
Load (%)	≥100% of 1 RM		
Range of motion			
Hip position (°)	80	0	80
Knee position (°)	130	110	20
Elongation stress	-50		+60
Angular velocity	Slow to moderate		
Uni-/bilateral exercise	Unilateral		
Kinetic chain	Open		

RM repetition maximum.

Table 2 Analysis of some of the currently most frequently used hamstring strengthening exercises (Fig. 3) to prevent strain injuries.

Parameters	Exercises								
	Nordic hamstring			Eccentric box drop			Single leg deadlift		
	Start position	Range of motion	End position	Start position	Range of motion	End position	Start position	Range of motion	End position
Contraction type	Eccentric (+)			Eccentric (+)			Eccentric (+)		
Load (%)	~Monitorable (±)			Non-monitorable (-)			~Monitorable (±)		
Range of motion									
Hip position (°)	0 (-)	0 (±)	0 (-)	0 (-)	130 (-)	130 (+)	0 (-)	90 (-)	90 (+)
Knee position (°)	90 (±)	90 (±)	0 (+)	0 (-)	-130 (-)	130 (-)	0 (-)	0 (-)	0 (+)
Elongation stress	-90 (±)		0 (-)	0 (-)		0 (-)	0 (-)		90 (+)
Angular velocity	Slow to moderate (+)			Moderate (+)			Slow to moderate (+)		
Uni-/bilateral exercise	Bilateral (-)			Bilateral (-)			Unilateral (+)		
Kinetic chain	~Open (±)			Closed (-)			~Closed (±)		

~ indicates the parameter characteristic is not optimally definable/applicable; no sign before a value indicates that the value is positive (i.e., the range of motion is in the direction of more elongation stress or the elongation stress is positive); - before a value indicates the value is negative (i.e., the range of motion is in the direction of less elongation stress or the elongation stress is negative); + after the value indicates the parameter corresponds to the new framework; ± after the value indicates the parameter is not optimal in regard to the new framework; - after the value indicates the parameter is non-specific to the new framework.

Fig. 3 Example of some of the hamstring strengthening exercises currently most frequently used to prevent strain injuries: **a** the Nordic hamstring; **b** the eccentric box drop; and **c** the single leg deadlift.

Finally, it should be noted that strain prevention is not only a question of strength but also depends on the timing of contraction, or a combination of both [11]. Neuromuscular control exercises targeting the lower extremities (e.g., running drills) and the lumbo-pelvic region (e.g., variations of trunk movements during running) have not been discussed in the present study, although two studies [13, 82] have suggested their potential contribution to hamstring strain injury prevention. However, further studies are needed to determine the exact role of the muscle contraction timing in the process of muscle strain.

References

1. Ekstrand J, Hagglund M, Walden M. Injury incidence and injury patterns in professional football: the UEFA injury study. Br J Sports Med. 2011;45(7):553–8.
2. Woods C, Hawkins RD, Maltby S, Hulse M, Thomas A, Hodson A, et al. The Football Association Medical Research Programme: an audit of injuries in professional football – analysis of hamstring injuries. Br J Sports Med. 2004;38(1):36–41.
3. Brooks JH, Fuller CW, Kemp SP, Reddin DB. Epidemiology of injuries in English professional rugby union: part 1 match injuries. Br J Sports Med. 2005;39(10):757–66.
4. Brooks JH, Fuller CW, Kemp SP, Reddin DB. Epidemiology of injuries in English professional rugby union: part 2 training injuries. Br J Sports Med. 2005;39(10):767–75.
5. Orchard J, Seward H. Epidemiology of injuries in the Australian Football League, seasons 1997-2000. Br J Sports Med. 2002;36(1):39–44.
6. Elliott MC, Zarins B, Powell JW, Kenyon CD. Hamstring muscle strains in professional football players: a 10-year review. Am J Sports Med. 2011;39(4):843–50.
7. Murphy JC, O'Malley E, Gissane C, Blake C. Incidence of injury in Gaelic football: a 4-year prospective study. Am J Sports Med. 2012;40(9):2113–20.
8. Alonso JM, Tscholl PM, Engebretsen L, Mountjoy M, Dvorak J, Junge A. Occurrence of injuries and illnesses during the 2009 IAAF World Athletics Championships. Br J Sports Med. 2010;44(15):1100–5.
9. Malliaropoulos N, Papacostas E, Kiritsi O, Papalada A, Gougoulias N, Maffulli N. Posterior thigh muscle injuries in elite track and field athletes. Am J Sports Med. 2010;38(9):1813–9.
10. Bennell KL, Crossley K. Musculoskeletal injuries in track and field: incidence, distribution and risk factors. Aust J Sci Med Sport. 1996;28(3):69–75.

11. Agre JC. Hamstring injuries. Proposed aetiological factors, prevention, and treatment. Sports Med. 1985;2(1):21–33.

12. Brooks JH, Fuller CW, Kemp SP, Reddin DB. Incidence, risk, and prevention of hamstring muscle injuries in professional rugby union. Am J Sports Med. 2006;34(8):1297–306.

13. Verrall GM, Slavotinek JP, Barnes PG. The effect of sports specific training on reducing the incidence of hamstring injuries in professional Australian Rules football players. Br J Sports Med. 2005;39(6):363–8.

14. Novacheck TF. The biomechanics of running. Gait Posture. 1998; 7(1):77–95.

15. Mann RA, Hagy J. Biomechanics of walking, running, and sprinting. Am J Sports Med. 1980;8(5):345–50.

16. Chumanov ES, Schache AG, Heiderscheit BC, Thelen DG. Hamstrings are most susceptible to injury during the late swing phase of sprinting. Br J Sports Med. 2012;46(2):90.

17. Orchard JW. Hamstrings are most susceptible to injury during the early stance phase of sprinting. Br J Sports Med. 2012;46(2):88–9.

18. Chumanov ES, Heiderscheit BC, Thelen DG. Hamstring musculotendon dynamics during stance and swing phases of high-speed running. Med Sci Sports Exerc. 2011;43(3):525–32.

19. Schache AG, Dorn TW, Blanch PD, Brown NA, Pandy MG. Mechanics of the human hamstring muscles during sprinting. Med Sci Sports Exerc. 2012;44(4):647–58.

20. Heiderscheit BC, Hoerth DM, Chumanov ES, Swanson SC, Thelen BJ, Thelen DG. Identifying the time of occurrence of a hamstring strain injury during treadmill running: a case study. Clin Biomech (Bristol, Avon). 2005;20(10):1072–8.

21. Schache AG, Wrigley TV, Baker R, Pandy MG. Biomechanical response to hamstring muscle strain injury. Gait Posture. 2009;29(2):332–8.

22. Thelen DG, Chumanov ES, Best TM, Swanson SC, Heiderscheit BC. Simulation of biceps femoris musculotendon mechanics during the swing phase of sprinting. Med Sci Sports Exerc. 2005;37(11):1931–8.

23. Petersen J, Holmich P. Evidence based prevention of hamstring injuries in sport. Br J Sports Med. 2005;39(6):319–23.

24. Wood SA, Morgan DL, Proske U. Effects of repeated eccentric contractions on structure and mechanical properties of toad sartorius muscle. Am J Physiol. 1993;265(3 Pt 1):C792–800.

25. Lieber RL, Woodburn TM, Friden J. Muscle damage induced by eccentric contractions of 25% strain. J Appl Physiol. 1991;70(6):2498–507.

26. Askling CM, Tengvar M, Saartok T, Thorstensson A. Acute first-time hamstring strains during high-speed running: a longitudinal study including clinical and magnetic resonance imaging findings. Am J Sports Med. 2007;35(2):197–206.

27. Koulouris G, Connell D. Evaluation of the hamstring muscle complex following acute injury. Skeletal Radiol. 2003;32(10):582–9.

28. Verrall GM, Slavotinek JP, Barnes PG, Fon GT, Spriggins AJ. Clinical risk factors for hamstring muscle strain injury: a prospective study with correlation of injury by magnetic resonance imaging. Br J Sports Med. 2001;35(6):435–9 (discussion 40).

29. Orchard J, Marsden J, Lord S, Garlick D. Preseason hamstring muscle weakness associated with hamstring muscle injury in Australian footballers. Am J Sports Med. 1997;25(1):81–5.

30. Yamamoto T. Relationship between hamstring strains and leg muscle strength. A follow-up study of collegiate track and field athletes. J Sports Med Phys Fitness. 1993;33(2):194–9.

31. Jonhagen S, Nemeth G, Eriksson E. Hamstring injuries in sprinters. The role of concentric and eccentric hamstring muscle strength and flexibility. Am J Sports Med. 1994;22(2):262–6.

32. Zakas A. Bilateral isokinetic peak torque of quadriceps and hamstring muscles in professional soccer players with dominance on one or both two sides. J Sports Med Phys Fitness. 2006;46(1):28–35.

33. Croisier JL, Ganteaume S, Binet J, Genty M, Ferret JM. Strength imbalances and prevention of hamstring injury in professional soccer players: a prospective study. Am J Sports Med. 2008;36(8):1469–75.

34. Brockett CL, Morgan DL, Proske U. Predicting hamstring strain injury in elite athletes. Med Sci Sports Exerc. 2004;36(3):379–87.

35. Proske U, Morgan DL, Brockett CL, Percival P. Identifying athletes at risk of hamstring strains and how to protect them. Clin Exp Pharmacol Physiol. 2004;31(8):546–50.

36. Brughelli M, Cronin J. Altering the length-tension relationship with eccentric exercise: implications for performance and injury. Sports Med. 2007;37(9):807–26.

37. Arnason A, Andersen TE, Holme I, Engebretsen L, Bahr R. Prevention of hamstring strains in elite soccer: an intervention study. Scand J Med Sci Sports. 2008;18(1):40–8.

38. Askling C, Karlsson J, Thorstensson A. Hamstring injury occurrence in elite soccer players after preseason strength training with eccentric overload. Scand J Med Sci Sports. 2003;13(4):244–50.

39. Gabbe BJ, Branson R, Bennell KL. A pilot randomised controlled trial of eccentric exercise to prevent hamstring injuries in community-level Australian Football. J Sci Med Sport. 2006;9(1–2):103–9.

40. Petersen J, Thorborg K, Nielsen MB, Budtz-Jorgensen E, Holmich P. Preventive effect of eccentric training on acute hamstring injuries in men's soccer: a cluster-randomized controlled trial. Am J Sports Med. 2011;39(11):2296–303.

41. Potier TG, Alexander CM, Seynnes OR. Effects of eccentric strength training on biceps femoris muscle architecture and knee joint range of movement. Eur J Appl Physiol. 2009;105(6):939–44.

42. Mjolsnes R, Arnason A, Osthagen T, Raastad T, Bahr R. A 10-week randomized trial comparing eccentric vs. concentric hamstring strength training in well-trained soccer players. Scand J Med Sci Sports. 2004;14(5):311–7.

43. Kilgallon M, Donnelly AE, Shafat A. Progressive resistance training temporarily alters hamstring torque-angle relationship. Scand J Med Sci Sports. 2007;17(1):18–24.

44. Brockett CL, Morgan DL, Proske U. Human hamstring muscles adapt to eccentric exercise by changing optimum length. Med Sci Sports Exerc. 2001;33(5):783–90.

45. Clark R, Bryant A, Culgan JP, Hartley B. The effects of eccentric hamstring strength training on dynamic jumping performance and isokinetic strength parameters: a pilot study on the implications for the prevention of hamstring injuries. Phys Ther Sport. 2005;6(2):67–73.

46. Iga J, Fruer CS, Deighan M, Croix MD, James DV. 'Nordic' hamstrings exercise – engagement characteristics and training responses. Int J Sports Med. 2012;33(12):1000–4.

47. Tomberlin JP, Basford JR, Schwen EE, Orte PA, Scott SC, Laughman RK, et al. Comparative study of isokinetic eccentric and concentric quadriceps training. J Orthop Sports Phys Ther. 1991;14(1):31–6.

48. Seger JY, Arvidsson B, Thorstensson A. Specific effects of eccentric and concentric training on muscle strength and morphology in humans. Eur J Appl Physiol Occup Physiol. 1998;79(1):49–57.

49. Brughelli M, Mendiguchia J, Nosaka K, Idoate F, Arcos AL, Cronin J. Effects of eccentric exercise on optimum length of the knee flexors and extensors during the preseason in professional soccer players. Phys Ther Sport. 2010;11(2):50–5.

50. Morgan DL, Proske U. Popping sarcomere hypothesis explains stretch-induced muscle damage. Clin Exp Pharmacol Physiol. 2004;31(8):541–5.

51. Whitehead NP, Morgan DL, Gregory JE, Proske U. Rises in whole muscle passive tension of mammalian muscle after eccentric contractions at different lengths. J Appl Physiol. 2003;95(3):1224–34.

52. Morgan DL. New insights into the behavior of muscle during active lengthening. Biophys J. 1990;57(2):209–21.

53. Blazevich AJ, Cannavan D, Coleman DR, Horne S. Influence of concentric and eccentric resistance training on architectural adaptation in human quadriceps muscles. J Appl Physiol. 2007;103(5):1565–75.

54. Seynnes OR, de Boer M, Narici MV. Early skeletal muscle hypertrophy and architectural changes in response to high-intensity resistance training. J Appl Physiol. 2007;102(1):368–73.

55. Garrett WE Jr, Safran MR, Seaber AV, Glisson RR, Ribbeck BM. Biomechanical comparison of stimulated and non-stimulated skeletal muscle pulled to failure. Am J Sports Med. 1987;15(5):448–54.

56. Sale DG. Neural adaptation to resistance training. Med Sci Sports Exerc. 1988;20(5 Suppl):S135–45.

57. Moritani T, deVries HA. Neural factors versus hypertrophy in the time course of muscle strength gain. Am J Phys Med. 1979;58(3):115–30.

58. Carroll TJ, Abernethy PJ, Logan PA, Barber M, McEniery MT. Resistance training frequency: strength and myosin heavy chain responses to two and three bouts per week. Eur J Appl Physiol Occup Physiol. 1998;78(3):270–5.

59. McDonagh MJ, Davies CT. Adaptive response of mammalian skeletal muscle to exercise with high loads. Eur J Appl Physiol Occup Physiol. 1984;52(2):139–55.

60. Hakkinen K, Alen M, Komi PV. Changes in isometric force- and relaxation-time, electromyographic and muscle fibre characteristics of human skeletal muscle during strength training and detraining. Acta Physiol Scand. 1985;125(4):573–85.

61. Campos GE, Luecke TJ, Wendeln HK, Toma K, Hagerman FC, Murray TF, et al. Muscular adaptations in response to three different resistance-training regimens: specificity of repetition maximum training zones. Eur J Appl Physiol. 2002;88(1–2):50–60.

62. American College of Sports Medicine. American College of Sports Medicine position stand. Progression models in resistance training for healthy adults. Med Sci Sports Exerc. 2009;41(3):687–708.

63. Hollander DB, Kraemer RR, Kilpatrick MW, Ramadan ZG, Reeves GV, Francois M, et al. Maximal eccentric and concentric strength discrepancies between young men and women for dynamic resistance exercise. J Strength Cond Res. 2007;21(1):34–40.

64. Kaminski TW, Wabbersen CV, Murphy RM. Concentric versus enhanced eccentric hamstring strength training: clinical implications. J Athl Train. 1998;33(3):216–21.

65. Guex K, Degache F, Gremion G, Millet GP. Effect of hip flexion angle on hamstring optimum length after a single set of concentric contractions. J Sports Sci. Epub 2013 Apr 30. doi 10.1080/02640414.2013.786186

66. Guex K, Gojanovic B, Millet GP. Influence of hip-flexion angle on hamstrings isokinetic activity in sprinters. J Athl Train. 2012;47(4):390–5.

67. Thelen DG, Chumanov ES, Hoerth DM, Best TM, Swanson SC, Li L, et al. Hamstring muscle kinematics during treadmill sprinting. Med Sci Sports Exerc. 2005;37(1):108–14.

68. Chleboun GS, France AR, Crill MT, Braddock HK, Howell JN. In vivo measurement of fascicle length and pennation angle of the human biceps femoris muscle. Cells Tissues Organs. 2001;169(4):401–9.

69. Visser JJ, Hoogkamer JE, Bobbert MF, Huijing PA. Length and moment arm of human leg muscles as a function of knee and hip-joint angles. Eur J Appl Physiol Occup Physiol. 1990;61(5–6):453–60.

70. Malliaropoulos N, Mendiguchia J, Pehlivanidis H, Papadopoulou S, Valle X, Malliaras P, et al. Hamstring exercises for track and field athletes: injury and exercise biomechanics, and possible implications for exercise selection and primary prevention. Br J Sports Med. 2012;46(12):846–51.

71. Brughelli M, Cronin J. Preventing hamstring injuries in sport. Strength Cond J. 2008;30(1):55–64.

72. Oliver GD, Dougherty CP. The razor curl: a functional approach to hamstring training. J Strength Cond Res. 2009;23(2):401–5.

73. Schmitt B, Tim T, McHugh M. Hamstring injury rehabilitation and prevention of reinjury using lengthened state eccentric training: a new concept. Int J Sports Phys Ther. 2012;7(3):333–41.

74. Kivi DM, Maraj BK, Gervais P. A kinematic analysis of high-speed treadmill sprinting over a range of velocities. Med Sci Sports Exerc. 2002;34(4):662–6.

75. Yu B, Queen RM, Abbey AN, Liu Y, Moorman CT, Garrett WE. Hamstring muscle kinematics and activation during overground sprinting. J Biomech. 2008;41(15):3121–6.

76. Mizuno T, Matsumoto M, Umemura Y. Decrements in stiffness are restored within 10 min. Int J Sports Med. 2013;34(6):484–90.

77. Paddon-Jones D, Leveritt M, Lonergan A, Abernethy P. Adaptation to chronic eccentric exercise in humans: the influence of contraction velocity. Eur J Appl Physiol. 2001;85(5):466–71.

78. Schache AG, Blanch P, Rath D, Wrigley T, Bennell K. Three-dimensional angular kinematics of the lumbar spine and pelvis during running. Hum Mov Sci. 2002;21(2):273–93.

79. Steindler A. Kinesiology of the human body under normal and pathological conditions. Springfield: Charles C Thomas; 1955.

80. Lutz GE, Palmitier RA, An KN, Chao EY. Comparison of tibiofemoral joint forces during open-kinetic-chain and closed-kinetic-chain exercises. J Bone Joint Surg Am. 1993;75(5):732–9.

81. Mayer F, Schlumberger A, van Cingel R, Henrotin Y, Laube W, Schmidtbleicher D. Training and testing in open versus closed kinetic chain. Isokinet Exerc Sci. 2003;11(4):181–7.

82. Cameron ML, Adams RD, Maher CG, Misson D. Effect of the HamSprint Drills training programme on lower limb neuromuscular control in Australian football players. J Sci Med Sport. 2009;12(1):24–30.

5.6. Article 6

Guex, K., Lugrin, V., Borloz, S. & Millet, G. P. (2014). Influence of a 6-weeks eccentric training on hamstring functional parameters and injury incidence in sprinters during a winter season. Soumis.

Abstract

Background: Hamstring strain injuries are common in sprinters. By improving several risk factors, eccentric strength training was shown to reduce hamstring injury rate. ***Purpose:*** The study aimed to assess how an additional hamstring eccentric strength training during the beginning of the winter preparation influences hamstring functional parameters (i.e., strength, hamstring-to-quadriceps ratio, optimum angle, flexibility) and injury incidence in sprinters who planned to compete during the indoor season. ***Study Design:*** Randomized control trial. ***Methods:*** Twenty sprinters were randomly allocated to an eccentric group (n = 10) or a control group (n = 10). Both groups performed their usual track and field training throughout the winter season. Sprinters in the eccentric group performed an additional 6-weeks hamstring eccentric program. Hamstring functional parameters were assessed before and after the intervention and injuries were recorded throughout the whole winter season (18 weeks). ***Results:*** In regard to usual training, the additional hamstring eccentric training increased (*a*) hamstring peak torques in concentric at 60°/s by 15% (F = 14.118, P < 0.001), eccentric at 30°/s by 18% (F = 9.290, P = 0.004) and at 120°/s by 20% (F = 15.539, P < 0.001), (*b*) conventional (F = 11.365, P = 0.002) and functional (F = 11.083, P = 0.002) ratios by 11%, and (*c*) flexibility by 4° (F = 5.025, P = 0.031). In the control group, three athletes sustained a hamstring injury (incidence of 30% and 1.99 per 1000 h) that occurred after 92.0 ± 27.2 h of exposure and resulted in 23.3 ± 16.1 days of lost time. In the eccentric group, two athletes sustained a hamstring injury (incidence of 20% and 1.28 per 1000 h) that occurred after 140.3 ± 5.3 h of exposure and resulted in 14.5 ± 0.7 days of lost time. In regard to non-injured leg, injured hamstrings were found weaker in concentric at 60°/s (-13%, P = 0.013) and eccentric at 30°/s (-7%, P = 0.037), with a lower conventional ratio (-13%, P < 0.001) and a shorter optimum length (+11°, P = 0.025). ***Conclusions:*** Six weeks of hamstring eccentric training performed at the commencement of the winter preparation improved several hamstring functional parameters in sprinters. Incidence and severity of injured hamstrings seemed reduced after the eccentric training, while exposure time before injury seemed increased. ***Key Terms:*** hamstring; injury; eccentric; isokinetic; flexibility; track and field.

Introduction

Hamstring strain injury is a common injury in track and field, especially during sprinting events. Two previous, prospective studies on sprinters have reported incidences of 18% and 20% within one-year of follow-up.[42, 47] The majority of injuries occur during the beginning of the season with the transition to increasing training volume and intensity.[47] Despite a low time spent in competition in comparison to training, injury incidence during competitions has been reported to be high: on average, one of 12 registered athletes incurred an injury during international athletic championships.[18] In sprinters, up to 50% of all hamstring injuries were shown to occur during competitions.[17, 47] These results suggest that insufficient preparation for maximal intensity activities, including sprint trainings and competitions, may be an injury risk factor and that exercise intensity *per se* may be more important than training volume.

The main role of the hamstring muscle group during sprinting is to decelerate knee extension during the late swing phase. During this phase, the hamstrings undergo active lengthening contraction (i.e., eccentric) while the hip is flexed and the knee is extending which induces substantial elongation stress on the biarticular hamstrings.[24, 40] This particular period of the sprinting gate cycle is reported to be the principal moment that hamstring injuries occur.[13] A number of risk factors, such as weakness,[27, 36, 46] bilateral asymmetry,[42, 48] lower hamstring-to-quadriceps ratio (H:Q ratio),[15, 42, 47] and decrease in optimum length,[9, 11] have been described. These risk factors, have been shown to be improved following interventions based on eccentric strength training,[3, 8, 26, 29, 32, 38] with a consecutive reduction in the hamstring injury rate.[1, 3, 10, 22, 37] The role of flexibility has also been discussed. While some studies have reported a relationship between poor hamstring flexibility and increased risk of injury in soccer players,[7, 25, 45] other reports have not found any relationship in sprinters, Australian footballers or soccer players.[2-4, 21, 36, 47] Nevertheless, eccentric resistance training increases hamstring flexibility.[34, 38] It seems logical, then, that the optimum angle (i.e., the angle at which peak torque occurred) was shown to be shifted in the direction of longer muscle length after eccentric intervention.[8, 12, 29, 31]

To our knowledge, it is unknown how a classical track and field training program based on sprint, endurance and strength trainings influences hamstring strength and flexibility in sprinters at the commencement of the preparation phase for an indoor season. In addition, how additional hamstring eccentric training influences the muscle's characteristics of the sprinters is also not understood. Therefore, the aim of this study was to assess the evolution of the muscle's characteristics after normal sprint training and how the characteristics adapt to an additional eccentric intervention. Indoor competitions take place after a relatively short preparation period and therefore could generate a high incidence of hamstring injuries, as a high intensity in training must be reached in a relatively short amount of time (i.e., in a few months). Thus, the present study aimed to examine the incidence of hamstring injuries in sprinters during a winter season. To our knowledge, this would be the first prospective study to focus on this particular period of the track and field season. Furthermore, analyses of strength and flexibility characteristics of injured hamstrings were performed. It was hypothesized (*a*) that normal training would not modify the hamstring strength and flexibility characteristics, whereas an additional eccentric intervention would improve the different risk factors for injury presented above, and (*b*) that the incidence of hamstring injuries would be high because of the intensity-based trainings. However, it was expected that the eccentric intervention would decrease this incidence.

Materials and methods

Subjects

Twenty national-level sprinters (7 men, 13 women; age, 20.0 ± 3.0 years; height, 173.4 ± 7.0 cm; body mass, 63.8 ± 7.6 kg) were recruited before the beginning of winter preparation for the 2014 indoor season. They were then randomly assigned to either an eccentric group or a control group. Table 1 shows the characteristics of the two groups. To be included, participants had to be short-track sprinters (100-200 m), long-track sprinters (400 m) or hurdlers (100/110-400 m hurdles) and committed to compete during the indoor season. They were excluded if they had sustained a hamstring injury in the 3 months before the commencement of the study. Participants signed an informed consent after explanation of the study protocol, data collection procedures and significance of the study objectives. Ethical approval for the project was obtained from the local committee on human research (Commission cantonale d'éthique de la recherché sur l'être humain, CER-VD, Agreement 90/13, Lausanne, Switzerland).

Table 1. Characteristics (mean ± SD) of the control and eccentric groups.

	Control group (n = 10)		Eccentric group (n = 10)	
	Women (n = 6)	Men (n = 4)	Women (n = 7)	Men (n = 3)
Age, years	20.7 ± 2.7	16.5 ± 0.6	21.6 ± 3.2	19.7 ± 1.2
Height, cm	167.6 ± 4.8	179.5 ± 4.8	172.1 ± 5.6	179.7 ± 5.9
Weight, kg	59.3 ± 7.3	72.7 ± 4.2	60.0 ± 3.9	69.8 ± 4.4
Body mass index, kg/m^2	21.0 ± 1.8	22.6 ± 2.1	20.2 ± 0.9	21.6 ± 0.7

Study design

Figure 1 presents the study design. The experiment lasted for 18 weeks. All participants performed an isokinetic and a flexibility assessment during the week prior to the beginning of the general preparation phase (pre-intervention assessment) after 3-4 weeks of inter-season recovery.

Both groups performed their usual track and field training throughout the study. The eccentric group performed additional hamstring eccentric exercises during the first six weeks of training (i.e., general and specific preparation phases). After these six weeks, all participants performed a second isokinetic and flexibility assessment (post-intervention assessment). Data from all hamstring injuries resulting from training or competition were recorded from the beginning of the preparation phase to the end of the indoor competition phase.

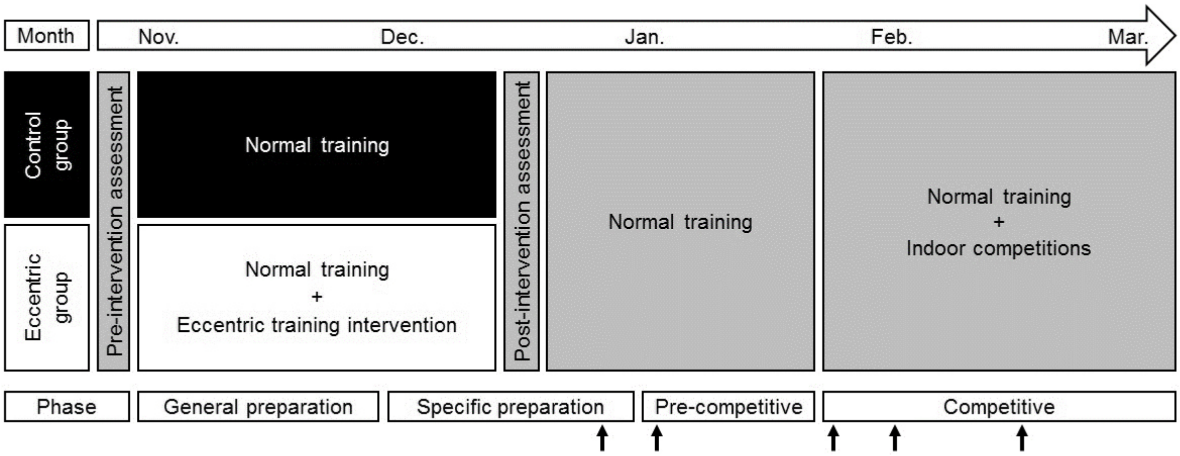


Figure 1. The eccentric group performed the eccentric training intervention during the general/specific preparation phase. Arrows represents the time of hamstring injuries.

Eccentric training intervention

The eccentric training protocol is presented in Table 2. During each session, two specific exercises were performed: the eccentric knee extension (EKE) (Figure 2, A) was executed on a traditional hamstring curl machine (Cybex, Lumex, Ronkonkoma, NY, USA), and the eccentric hip flexion (EHF) (Figure 2, B) was performed on a hip trainer machine (Schnell, Peutenhausen, Germany). Eccentric phases of both exercises were performed with the left and right leg separately, while a partner assisted during the concentric phases. During EKE, the hip was positioned at an angle of 0° and the knee range of motion was fixed at 120° (i.e., from 120° to 0°

of knee flexion). During EHF, the knee was held at an angle of 0° and the hip range of motion was performed at approximately 80° depending on the athlete's hamstring flexibility (i.e., from 0° to ~80° of hip flexion). The elongation stress on the biarticular hamstrings can be estimated by subtracting the knee flexion angle from the hip flexion angle.[24] Therefore, the elongation stress was negative (from -120 to 0) during the EKE, while it was positive (from 0 to ~80) during the EHF. Together, these two exercises cover the whole hamstring length-tension relationship. One repetition maximum (1-RM) of each subject was tested during the first training session of weeks one and four. Training loads were based and adjusted on these 1-RM values as shown in Table 2. High loads were chosen according to the recommendations on hamstring strains prevention.[24]

Table 2. Eccentric training intervention for the eccentric group.

Week	Sessions per week	Exercises	Sets and reps per exercise	Load [% of 1-RM]
1	1 + 1-RM test	EKE + EHF	2 x 12	80%
2	2	EKE + EHF	2 x 10	90%
3	2	EKE + EHF	2 x 8	100%
4	2 + 1-RM test	EKE + EHF	3 x 10	90%
5	2	EKE + EHF	3 x 8	100%
6	2	EKE + EHF	3 x 6	110%

RM, repetition maximum; EKE, eccentric knee extension; EHF, eccentric hip flexion.

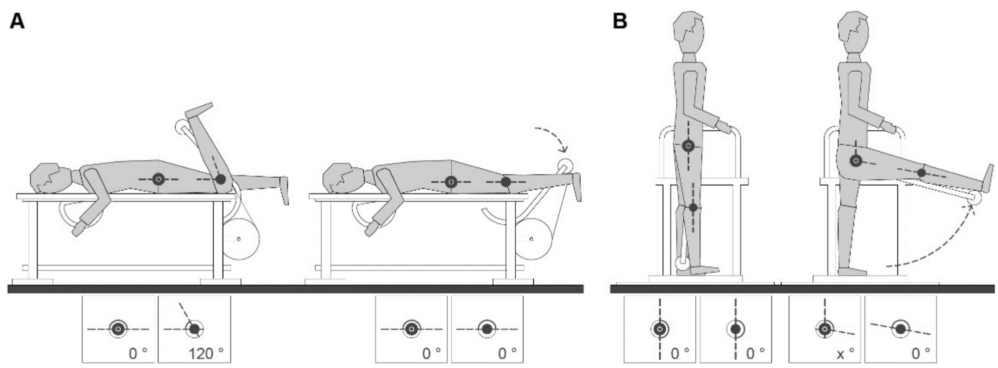


Figure 2. Eccentric knee extension (A) and eccentric hip flexion (B).

Isokinetic and flexibility measurements

Pre- and post-assessments consisted of a hamstring flexibility measurement followed by a hamstring and quadriceps isokinetic strength test on both dominant (the leg used to kick a ball) and non-dominant legs. Prior to the pre-assessment, each subject performed a standardized familiarization session, which consisted of 10 concentric knee flexion-extensions at 240°/s followed by 10 eccentric knee extensions at 120°/s with a 90-sec rest between the two tests.

Prior to the testing procedures, the participants performed a standardized 10 min warm-up on a cycling ergometer (60 rpm, 80 watts). Hamstring flexibility was then measured using the passive knee extension test (PKE).[19] Afterward, athletes were placed on an isokinetic dynamometer (Humac Norm, Humac, CA, USA), with stabilization straps positioned across their chest, pelvis, and ipsilateral thigh. The dynamometer was calibrated according to the manufacturer's recommendations, and instructions were followed for optimal reproducibility. The hip flexion angle was held at 80°,[23] while the knee range of motion was fixed at 100° (i.e., between 0° and 100° of knee flexion). Before testing, gravity correction was obtained by measuring the torque exerted on the lever arm shin-pad with the knee held in a relaxed state in extension.

The isokinetic strength test consisted of (*a*) four maximal concentric knee flexion-extensions at 60°/s, (*b*) five maximal concentric knee flexion-extensions at 240°/s, (*c*) four maximal eccentric knee extensions at 30°/s, and (*d*) five maximal eccentric knee extensions at 120°/s. A 3-min rest separated each condition, and an 8-min rest was completed between both side assessments. Left and right legs were tested in a randomized order, but this order was kept the same in pre- and post-assessments. All athletes were verbally encouraged to work as hard as possible from the first to the last repetition.

Injury recording

All participants were asked to report to investigators if they had missed any training or competition due to hamstring injury during the 2014 winter season. Investigators were in daily contact with coaches and athletes throughout the investigation period. Hamstring injury was defined as any physical complaint localized in the posterior thigh produced by an energy transfer experienced or sustained by an athlete during participation in athletics training or competition regardless of whether it received medical attention or its consequences with respect to impairments in connection with competition or training.[43] The date of injury, the mechanism and the number of days before recommencement of normal training (i.e., time loss) were recorded.

Incidence was calculated by dividing the number of athletes injured during the 18 weeks of the experiment by the athletes' total number. Then, incidence in relation to exposure was calculated as the number of injuries recorded during the study period divided by the athletes' total exposure hours (per 1000 h of athletic practice). The athletes' total exposure hours was computed as the sum of recorded training and competition hours during the study period. [43]

The injury severity was defined as the number of days that have elapsed from the day after the onset of the injury to the day of the athlete's return to full participation in athletics training and become fully available for competition. [43] Injuries were reported as minor (1 to 7 days), moderately serious (8 to 28 days) or serious (≥ 29 days). [43]

Data analysis

Parameters of interest were values of hamstring peak torques per body weight (in Nm/kg) in concentric at 60°/s (Hcon60) and 240°/s (Hcon240), eccentric at 30°/s (Hecc30) and 120°/s (Hecc120); quadriceps in concentric at 60°/s (Qcon60) and 240°/s (Qcon240). In addition, H:Q ratios for Hcon60:Qcon60, Hcon240:Qcon240 and Hecc30:Qcon240 were calculated. Finally, values (in degree) of optimum angle for hamstring acting concentrically at 60°/s (OA Hcon60) and for knee flexion angle obtained with the PKE test were analyzed. For OA Hcon60 and PKE, 0° corresponds to full knee extension.

Statistical analysis

Mean and standard deviation (SD) were calculated for all parameters. Data were screened for a normal distribution using Shapiro-Wilk normality tests. Two-way [time (pre- vs. post-) x group (control vs. eccentric)] analysis of variance (ANOVA) with repeated measures were used (*a*) to analyze the effect of the eccentric training intervention, (*b*) to compare injured vs. non-injured legs in injured athletes, and (*c*) to compare non-dominant vs. dominant legs in non-injured and injured athletes separately. Tukey post-hoc tests were used to localize the differences between means. For all statistical analysis, significance was set at $P < 0.05$. Statistical analysis was performed with SigmaPlot 12.5 (Systat Software Inc., San Jose, CA).

Results

Eccentric training intervention

The eccentric group completed 10.7 ± 0.7 hamstring eccentric strength sessions throughout the six weeks' training period (97% participation rate). There was no difference in the total amount of other training contents (i.e., sprint, endurance and strength trainings) between groups. Since there were no significant difference between right and left legs for any of the parameters of interest (P > 0.05), the values for both legs were combined into a single group. The values of peak torques, H:Q ratios and knee flexion angles are presented in Table 3.

Table 3. Values (mean ± SD) of peak torques per body weight, hamstring-to-quadriceps ratios and knee flexion angles for the control and eccentric groups before (Pre-) and after (Post-) the eccentric training intervention.

	Control group (n = 10)			Eccentric group (n = 10)			
	Pre-	Post-		Pre-		Post-	
Peak torque, Nm/kg							
Hcon60	1.73 ± 0.29	1.74 ± 0.32		1.51 ± 0.20	#	1.74 ± 0.24	***
Hcon240	1.41 ± 0.22	1.44 ± 0.24		1.30 ± 0.18		1.40 ± 0.14	**
Hecc30	2.21 ± 0.46	2.32 ± 0.48	*	1.80 ± 0.31	##	2.13 ± 0.28	***
Hecc120	2.23 ± 0.39	2.35 ± 0.38	**	1.89 ± 0.32	##	2.26 ± 0.24	***
Qcon60	2.93 ± 0.40	3.01 ± 0.39		2.75 ± 0.51		2.85 ± 0.55	
Qcon240	1.77 ± 0.23	1.89 ± 0.21	**	1.68 ± 0.35		1.79 ± 0.31	*
H:Q Ratio							
Hcon60:Qcon60	0.60 ± 0.10	0.58 ± 0.09		0.56 ± 0.08		0.62 ± 0.10	***
Hcon240:Qcon240	0.80 ± 0.11	0.77 ± 0.12		0.78 ± 0.11		0.80 ± 0.10	
Hecc30:Qcon240	1.24 ± 0.20	1.23 ± 0.23		1.09 ± 0.21	#	1.21 ± 0.21	***
Knee flexion, °							
OA Hcon60	40.9 ± 10.3	41.6 ± 11.6		42.3 ± 17.4		38.3 ± 16.4	
PKE	51.9 ± 6.9	51.8 ± 8.1		56.1 ± 8.8		51.8 ± 5.4	**

H, hamstring; Q, quadriceps; con, concentric; ecc, eccentric; OA, optimum angle; PKE, passive knee extension test. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$ for differences with pre-training, # $P < 0.05$, ## $P < 0.01$ for differences with control group.

In the eccentric group, following the eccentric training intervention, peak torque increased in Hcon60 (15%, $P < 0.001$), Hcon240 (8%, $P = 0.002$), Hecc30 (18%, $P < 0.001$), Hecc120 (20%, $P < 0.001$) and Qcon240 (7%, $P = 0.013$), but did not change in Qcon60 ($P > 0.05$). In the control group, peak torque increased in Hecc30 (5%, $P = 0.022$), Hecc120 (6%, $P = 0.007$) and Qcon240 (7%, $P = 0.009$), but did not change in Hcon60, Hcon240 and Qcon60 ($P > 0.05$). Group-by-time interactions were observed for peak torque in Hcon60 ($F = 14.118$, $P < 0.001$), Hecc30 ($F = 9.290$, $P = 0.004$) and Hecc120 ($F = 15.539$, $P < 0.001$).

In the eccentric group, Hcon60:Qcon60 and Hecc30:Qcon240 ratios were both improved ($P < 0.001$) after the eccentric training by 11%. Hcon240:Qcon240 ratio did not change from pre- to post-. In the control group, the three ratios were not modified after the intervention. Group-by-time interactions were observed for Hcon60:Qcon60 ($F = 11.365$, $P = 0.002$) and Hecc30:Qcon240 ($F = 11.083$, $P = 0.002$) ratios.

Following the intervention, PKE of the eccentric group was modified by 4° ($P = 0.003$) in the direction of longer muscle length. OA Hcon60 was also modified by 4° in the same direction. However, this change was not significant. In the control group, both PKE and OA Hcon60 did not change from pre- to post-. Group-by-time interaction was observed for PKE ($F = 5.025$, $P = 0.031$).

Hamstring injuries

Hamstring injury occurred in one lower limb in five athletes (four women and one man) within the study period (incidence of 25% and 1.63 per 1000 h). The injured athletes' characteristics are presented in Table 4. Three injured athletes were part of the control group (incidence of 30% and 1.99 per 1000 h) and two in the eccentric group (incidence of 20% and 1.28 per 1000 h). The mean exposure time (training and competition) was 153.6 ± 16.9 h during the study. On average, the five injuries occurred after 111.4 ± 32.9 h of exposure (92.0 ± 27.2 h in the control group and 140.3 ± 5.3 h in the eccentric group). In term of training phase, one injury occurred at the very end of the specific preparation phase, one in pre-competitive phase and three in competitive phase (one during training and two during competitions) (Figure 1). It is of interest to note that no injury occurred during the eccentric training intervention. Three injuries were sustained while sprinting and two while hurdling. On average, injuries resulted in 19.8 ± 12.4 days of lost time (23.3 ± 16.1 days in the control group and 14.5 ± 0.7 days in the eccentric group). One injury was considered as minor (control group), two as moderately serious (eccentric group) and two as serious (control group). One injury (eccentric group) was a re-injury.

Table 5 presents all parameters of interest for the injured and non-injured legs of the five injured athletes. In pre-intervention assessment, injured legs' peak torque was lower than non-injured legs in Hecc30 (-10%, $P = 0.007$). The injured legs' Hcon60:Qcon60 ratio was lower than non-injured legs by 7% ($P = 0.015$). The five injured legs were weaker than non-injured legs in Hecc30.

In post-intervention assessment, injured legs' peak torque was lower than non-injured legs in Hcon60 (-13%, $P = 0.013$) and Hecc30 (-7%, $P = 0.037$). Injured legs' ratio Hcon60:Qcon60 was lower than non-injured legs by 13% ($P < 0.001$) and OA Hcon60 of injured legs was 11° higher (shorter muscle length) than non-injured legs ($P = 0.025$). The five injured legs were weaker than non-injured legs in Hcon60, Hecc30, Hecc120, Hcon60:Qcon60 ratio and OA Hcon60 (shorter muscle length).

Between pre- and post-, the injured legs' peak torque increased by 14% in Hecc30 ($P = 0.047$). Group-by-time interactions were observed for peak torque in Hcon60 ($F = 10.196$, $P = 0.033$) and for OA Hcon60 ($F = 13.576$, $P = 0.021$).

Finally, it is of interest to observe that in both non-injured and injured athletes there was no difference ($P > 0.05$) between non-dominant and dominant leg for any of the parameters of interest.

Table 4. Individual characteristics of the injured athletes.

Group	Sex	Age, years	Height, cm	Weight, kg	Main discipline	Exposure before injury, hours	Training phase	Mechanism of injury	Time loss, days	Severity of injury	Re-injury
CON	W	20	163	60.3	100 m	72	Specific preparation	Sprinting (training)	30	Serious	No
CON	M	17	187	68.6	100 m H	81	Pre-competitive	Hurdling (training)	35	Serious	No
CON	W	26	171	61.0	100 m	123	Competitive	Sprinting (competition)	5	Minor	No
ECC	W	24	183	65.3	400 m H	137	Competitive	Sprinting (competition)	15	Moderately serious	Yes
ECC	W	17	171	57.0	100 m H	144	Competitive	Hurdling (training)	14	Moderately serious	No

W, woman; M, man; H, hurdles; CON, control; ECC, eccentric.

Table 5. Values (mean ± SD) of peak torques per body weight, hamstring-to-quadriceps ratios and knee flexion before (Pre-) and after (Post-) the eccentric training intervention for non-injured and injured legs of athletes who sustained hamstring injuries.

	Non-injured leg (n = 5)		Injured leg (n = 5)				Imbalance	
	Pre-	Post-	Pre-		Post-		Pre-	Post-
Peak torque, Nm/kg								
Hcon60	1.68 ± 0.35	1.77 ± 0.37	1.55 ± 0.23		1.54 ± 0.27	*	4/5	5/5
Hcon240	1.43 ± 0.28	1.42 ± 0.30	1.41 ± 0.28		1.39 ± 0.22		3/5	3/5
Hecc30	2.00 ± 0.30	2.19 ± 0.40	1.80 ± 0.36	**	2.05 ± 0.38	*#	5/5	5/5
Hecc120	2.00 ± 0.38	2.21 ± 0.26	1.87 ± 0.38		2.08 ± 0.27		3/5	5/5
Qcon60	2.90 ± 0.23	3.12 ± 0.49	2.91 ± 0.30		3.13 ± 0.31			
Qcon240	1.80 ± 0.24	1.83 ± 0.19	1.70 ± 0.23		1.86 ± 0.24			
H:Q Ratio								
Hcon60:Qcon60	0.58 ± 0.14	0.57 ± 0.06	0.54 ± 0.11	*	0.49 ± 0.06	***	4/5	5/5
Hcon240:Qcon240	0.79 ± 0.08	0.77 ± 0.12	0.84 ± 0.17		0.75 ± 0.05		3/5	3/5
Hecc30:Qcon240	1.11 ± 0.11	1.20 ± 0.17	1.06 ± 0.17		1.10 ± 0.14		4/5	4/5
Knee flexion, °								
OA Hcon60	39.2 ± 12.1	36.0 ± 11.4	39.4 ± 16.1		47.4 ± 11.6	*	2/5	5/5
PKE	54.8 ± 9.9	50.0 ± 12.3	50.0 ± 7.9		47.6 ± 10.1		0/5	1/5

H, hamstring; Q, quadriceps; con, concentric; ecc, eccentric; OA, optimum angle; PKE, passive knee extension test. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$ for differences with non-injured leg; $^{\#}$ $P < 0.05$, for differences with pre-training assessment.

Discussion

The main finding of the present study is that a low volume of hamstring eccentric strength training performed at the commencement of winter preparation improved several hamstring injury risk factors; e.g., eccentric and concentric strength, H:Q ratios and flexibility. Hamstring injury incidence was found to be slightly lower in the eccentric group. Injuries were sustained later in the training process and resulted in less time loss in the eccentric group compared to the control group.

Eccentric training intervention

Hamstring injuries are reported to occur particularly during eccentric muscle contraction while sprinting.[13] Hence, improving eccentric strength may minimize the risk of injury. Previous studies have found an 11-38% increase in hamstring eccentric strength after 6-10 weeks (1-3 sessions per week) of hamstring eccentric training performed on a traditional hamstring curl, a YoYo flywheel ergometer, or using the Nordic hamstring exercise.[3, 26, 28, 32] Results of the present investigation are in line with these previous studies as, after eccentric training intervention, an improvement of 18% and 20% of hamstring eccentric strength was found at 30°/s and 120°/s, respectively. Moreover, although strength gains are known to be mainly mode specific,[16, 44] a 15% increase in hamstring concentric strength was also observed at 60°/s after the eccentric intervention. Kaminski et al.[28] have found a 29% increase in 1-RM after six weeks (two sessions per week) of hamstring eccentric training at 100% of 1-RM, suggesting that high-intensity eccentric training is efficient for improving both eccentric and concentric strength. Interestingly, in our control group, the eccentric hamstring strength increased by 5% and 6% at slow and fast angular velocities, respectively. This change was not expected, because no specific hamstring strength training was performed in this group. Thus, this outcome could be attributed to the running activity with the repetitive hamstring eccentric contractions at the end of each swing phase.

A low H:Q ratio has been identified as an important predictive risk factor for hamstring injury.[15] In the present study, the usual track and field training at the commencement of winter preparation without any specific hamstring strength training induced an increase in hamstring eccentric strength at both slow and fast angular velocities and in quadriceps concentric strength at fast angular velocity. With a similar strength enhancement in both agonist and antagonist muscles groups, the H:Q ratio was logically not modified, while two additional eccentric strength trainings of the hamstring per week were sufficient to significantly increase Hcon60:Qcon60 and Hecc30:Qcon240 ratios by 11%. These results are in line with the finding of Mjølsnes et al.[32] who reported an increase of 11% after 10 weeks (1-3 sessions per week) of Nordic hamstring exercise.

Optimum length and flexibility of the hamstring have been proposed as important injury risk factors.[7, 9, 11, 25, 45] In this study, both optimum angle and PKE were shifted by 4° in the direction of longer muscle length after the eccentric training intervention. However, only the change in PKE was significant. Several studies have found an increase in hamstring flexibility following eccentric resistance training:[34, 38] Potier et al.[38] explained this rise by an increase in fascicle length, suggesting an increase of sarcomeres in series within the muscle. This adaptation was not explored in the hamstring muscles, but was observed after eccentric training in human quadriceps.[6, 41] A higher number of sarcomeres in series within the muscle increased the fibers effective compliance series, leading to a shift of the whole muscle's length-tension relation in the direction of longer muscle length.[8] Several studies have observed a shift in optimum hamstring length in the direction of longer muscle length after an eccentric intervention.[8, 12, 14, 29, 31] However, Iga et al.[26] did not report this shift due to a large variability in results. In the present study, a similar high variability was observed and could explain the non-significant shift found after the eccentric training.

Hamstring injuries

Previous studies on hamstring injuries in sprinters have reported up to a 20% incidence within one year of follow-up,[42, 47] which is similar to our results, as one out of four athletes sustained a hamstring injury. However, this incidence was recorded during the winter season only. Consequently, the incidence in relation to exposure was almost twice as high (1.63 vs. 0.87 per 1000 h) than the results of Yeung et al.[47] This outcome may be explained by the short period of preparation (i.e., 2-3 months) before the indoor season when high intensity in training is reached over a short period of time. It is speculated that athletes who participate in the indoor season are less ready to undergo intensive activity than those who focus on the outdoor season. Two out of five athletes sustained an injury during competition. This result is in line with Yeung et al.[47] who reported 50% of injuries during competition and suggests that exposure to high-intensity activities, including sprint trainings and competitions, may be a more important injury risk factor than training volume.

Hamstring injury incidence seemed lower (20% vs. 30% and 1.28 vs. 1.99 per 1000 h) and injuries were sustained after 34% more exposure time, resulting in 38% less time loss in the eccentric group than in the control group. However, due to the low number of injured subjects, no statistical analysis was performed on these values. Even if the incidence appeared to be reduced after eccentric intervention, it was not lower than previous results in prospective studies on sprinters.[42, 47] In the present study, the eccentric training was only conducted during the first six weeks of the indoor season preparation. It would have been interesting to extend the intervention throughout the entire winter season to determine whether the two injuries would have been avoided in the eccentric group. However, because the origin of hamstring injury is multifactorial,[30, 35] interventions based only on the strength parameters would likely not prevent all hamstring injuries. Nevertheless, this type of intervention seems indispensable to minimizing the occurrence of hamstring injuries.

When examining the strength and flexibility parameters of injured athletes, one may note that at post-assessment the injured leg was 13% and 7% weaker than the non-injured leg in Hcon60 and Hecc30, respectively (even if the eccentric strength of injured hamstrings increased by 14% at 30°/s), Hcon60:Qcon60 ratio was 13% lower and OA Hcon60 was found at 11° shorter muscle length. At pre-assessment, only two parameters were found to be lower in the injured leg than in the non-injured one: Hecc30 and Hcon60:Qcon60 ratio. Therefore, because there was a large change in muscular performance over a relatively short period of time, we suggest performing an isokinetic assessment at the end of each training phase (i.e., general preparation, specific preparation and pre-competitive phases).

In the present study, the ability of isokinetic and flexibility measurements performed at the commencement and after six weeks of winter preparation to predict the risk of hamstring injury was not assessed because of the insufficient number of injured subjects. However, our results are consistent with other prospective investigations, because weaker concentric and eccentric strength and lower concentric flexion-extension ratio of injured hamstrings have been shown in athletes and Australian football players.[36, 42, 47] However, this point is still debated, because no relationship was reported between strength parameters and injury in other investigations.[5] The question of flexibility has been discussed even more, with some investigations reporting a relationship between poor hamstring flexibility and increased risk of injury,[7, 25, 45] while others reporting no relationship.[2-4, 21, 36, 47] In accordance with the latter reports, in the present study, flexibility of injured hamstrings did not differ from the non-injured legs.

To our knowledge, the present study is the first prospective study to report that injured hamstring had an optimum angle in a shorter muscle length position. It was shown previously that injured hamstring torque peaked at a 12° shorter muscle length than non-injured muscle.[9, 39] A shortened optimal length results in muscles operating to a greater extent on the descending part of torque-length relationships. This may predispose muscles to greater microscopic damage and post-exercise weakness as a consequence of hamstring eccentric contractions combined with a high elongation stress at the end of each swing phase during sprinting.[9, 24, 33, 39] An accumulation of such damage could lead to macroscopic muscle strain.[9, 33] Neuromuscular inhibition could explain the low concentric and eccentric strengths and the lower optimum length observed in injured legs. This mechanism has been discussed as a causative factor for hamstring re-injury.[20] One may think that this mechanism could also be responsible for a first time hamstring injury, as among the injured athletes in the present study only one was a re-injury.

The low number of participants is a limitation of the present study. Prospective investigations including a larger number of participants are needed to clarify possible relationships between potential risk factors and the subsequent occurrence of hamstring injury in sprinters. However, in comparison to team sports, it is challenging to gather large cohorts of subjects participating in track and field.

Conclusion

Hamstring injury rate was found to be high during a winter season focusing on indoor competitions. Six weeks of eccentric strength training during the general and specific preparation phases improved several potential injury risk factors, such as eccentric and concentric strength, H:Q ratio and flexibility. Consequently, incidence and severity of injured hamstrings seemed reduced after the eccentric training, while exposure time before injury seemed increased. Among injured athletes, injured hamstrings were found to be weaker in concentric and eccentric strength at slow angular velocity, with a lower conventional ratio and a shorter optimum length, whereas no difference in flexibility was observed. Finally, a single pre-season assessment is likely insufficient to detect athletes at risk of injury. It is suggested that isokinetic assessments be performed at the end of each training phase, because muscle functional parameters change relatively quickly during the training process.

References

1. Arnason A, Andersen TE, Holme I, Engebretsen L, Bahr R. Prevention of hamstring strains in elite soccer: an intervention study. Scand J Med Sci Sports. 2008;18(1):40-48.

2. Arnason A, Sigurdsson SB, Gudmundsson A, Holme I, Engebretsen L, Bahr R. Risk factors for injuries in football. Am J Sports Med. 2004;32(1 Suppl):5S-16S.

3. Askling C, Karlsson J, Thorstensson A. Hamstring injury occurrence in elite soccer players after preseason strength training with eccentric overload. Scand J Med Sci Sports. 2003;13(4):244-250.

4. Bennell K, Tully E, Harvey N. Does the toe-touch test predict hamstring injury in Australian Rules footballers? Aust J Physiother. 1999;45(2):103-109.

5. Bennell K, Wajswelner H, Lew P, et al. Isokinetic strength testing does not predict hamstring injury in Australian Rules footballers. Br J Sports Med. 1998;32(4):309-314.

6. Blazevich AJ, Cannavan D, Coleman DR, Horne S. Influence of concentric and eccentric resistance training on architectural adaptation in human quadriceps muscles. J Appl Physiol. 2007;103(5):1565-1575.

7. Bradley PS, Portas MD. The relationship between preseason range of motion and muscle strain injury in elite soccer players. J Strength Cond Res. 2007;21(4):1155-1159.

8. Brockett CL, Morgan DL, Proske U. Human hamstring muscles adapt to eccentric exercise by changing optimum length. Med Sci Sports Exerc. 2001;33(5):783-790.

9. Brockett CL, Morgan DL, Proske U. Predicting hamstring strain injury in elite athletes. Med Sci Sports Exerc. 2004;36(3):379-387.

10. Brooks JH, Fuller CW, Kemp SP, Reddin DB. Incidence, risk, and prevention of hamstring muscle injuries in professional rugby union. Am J Sports Med. 2006;34(8):1297-1306.

11. Brughelli M, Cronin J. Altering the length-tension relationship with eccentric exercise : implications for performance and injury. Sports Med. 2007;37(9):807-826.

12. Brughelli M, Mendiguchia J, Nosaka K, Idoate F, Arcos AL, Cronin J. Effects of eccentric exercise on optimum length of the knee flexors and extensors during the preseason in professional soccer players. Phys Ther Sport. 2010;11(2):50-55.

13. Chumanov ES, Schache AG, Heiderscheit BC, Thelen DG. Hamstrings are most susceptible to injury during the late swing phase of sprinting. Br J Sports Med. 2012;46(2):90.

14. Clark R, Bryant A, Culgan JP, Hartley B. The effects of eccentric hamstring strength training on dynamic jumping performance and isokinetic strength parameters: a pilot study on the implications for the prevention of hamstring injuries. Physical Therapy in Sport. 2005;6(2):67-73.

15. Croisier JL, Ganteaume S, Binet J, Genty M, Ferret JM. Strength imbalances and prevention of hamstring injury in professional soccer players: a prospective study. Am J Sports Med. 2008;36(8):1469-1475.

16. Duncan PW, Chandler JM, Cavanaugh DK, Johnson KR, Buehler AG. Mode and speed specificity of eccentric and concentric exercise training. J Orthop Sports Phys Ther. 1989;11(2):70-75.

17. Edouard P, Morel N, Serra JM, Pruvost J, Oullion R, Depiesse F. Prevention of musculoskeletal injuries in track and field. Review of epidemiological data. Science & Sports. 2011;26(6):307-315.

18. Feddermann-Demont N, Junge A, Edouard P, Branco P, Alonso JM. Injuries in 13 international Athletics championships between 2007-2012. Br J Sports Med. 2014;48(7):513-522.

19. Fredriksen H, Dagfinrud H, Jacobsen V, Maehlum S. Passive knee extension test to measure hamstring muscle tightness. Scand J Med Sci Sports. 1997;7(5):279-282.

20. Fyfe JJ, Opar DA, Williams MD, Shield AJ. The role of neuromuscular inhibition in hamstring strain injury recurrence. J Electromyogr Kinesiol. 2013;23(3):523-530.

21. Gabbe BJ, Bennell KL, Finch CF, Wajswelner H, Orchard JW. Predictors of hamstring injury at the elite level of Australian football. Scand J Med Sci Sports. 2006;16(1):7-13.

22. Gabbe BJ, Branson R, Bennell KL. A pilot randomised controlled trial of eccentric exercise to prevent hamstring injuries in community-level Australian Football. J Sci Med Sport. 2006;9(1-2):103-109.

23. Guex K, Gojanovic B, Millet GP. Influence of hip-flexion angle on hamstrings isokinetic activity in sprinters. J Athl Train. 2012;47(4):390-395.

24. Guex K, Millet GP. Conceptual Framework for Strengthening Exercises to Prevent Hamstring Strains. Sports Med. 2013;43(12):1207-1215.

25. Henderson G, Barnes CA, Portas MD. Factors associated with increased propensity for hamstring injury in English Premier League soccer players. J Sci Med Sport. 2010;13(4):397-402.

26. Iga J, Fruer CS, Deighan M, Croix MD, James DV. 'Nordic' hamstrings exercise - engagement characteristics and training responses. Int J Sports Med. 2012;33(12):1000-1004.

27. Jonhagen S, Nemeth G, Eriksson E. Hamstring injuries in sprinters. The role of concentric and eccentric hamstring muscle strength and flexibility. Am J Sports Med. 1994;22(2):262-266.

28. Kaminski TW, Wabbersen CV, Murphy RM. Concentric versus enhanced eccentric hamstring strength training: clinical implications. J Athl Train. 1998;33(3):216-221.

29. Kilgallon M, Donnelly AE, Shafat A. Progressive resistance training temporarily alters hamstring torque-angle relationship. Scand J Med Sci Sports. 2007;17(1):18-24.

30. Liu H, Garrett WE, Moorman CT, Yu B. Injury rate, mechanism, and risk factors of hamstring strain injuries in sports: A review of the literature. J Sport Health Sci. 2012;1(2):92-101.

31. Martínez-Ruiz E, Mendiguchia J, Rubio-Arias JA, Alcaraz PE, Esparza-Ros F. Effect of a prevention program for hamstring strain injury on optimum length of the knee flexors. IOC World Conference on Prevention of Injury & Illness in Sport. Vol 48. Monaco: Br J Sports Med; 2014:633.

32. Mjolsnes R, Arnason A, Osthagen T, Raastad T, Bahr R. A 10-week randomized trial comparing eccentric vs. concentric hamstring strength training in well-trained soccer players. Scand J Med Sci Sports. 2004;14(5):311-317.

33. Morgan DL. New insights into the behavior of muscle during active lengthening. Biophys J. 1990;57(2):209-221.

34. Nelson RT, Bandy WD. Eccentric Training and Static Stretching Improve Hamstring Flexibility of High School Males. J Athl Train. 2004;39(3):254-258.

35. Opar DA, Williams MD, Shield AJ. Hamstring strain injuries: factors that lead to injury and re-injury. Sports Med. 2012;42(3):209-226.

36. Orchard J, Marsden J, Lord S, Garlick D. Preseason hamstring muscle weakness associated with hamstring muscle injury in Australian footballers. Am J Sports Med. 1997;25(1):81-85.

37. Petersen J, Thorborg K, Nielsen MB, Budtz-Jorgensen E, Holmich P. Preventive effect of eccentric training on acute hamstring injuries in men's soccer: a cluster-randomized controlled trial. Am J Sports Med. 2011;39(11):2296-2303.

38. Potier TG, Alexander CM, Seynnes OR. Effects of eccentric strength training on biceps femoris muscle architecture and knee joint range of movement. Eur J Appl Physiol. 2009;105(6):939-944.

39. Proske U, Morgan DL, Brockett CL, Percival P. Identifying athletes at risk of hamstring strains and how to protect them. Clin Exp Pharmacol Physiol. 2004;31(8):546-550.

40. Schache AG, Dorn TW, Blanch PD, Brown NA, Pandy MG. Mechanics of the human hamstring muscles during sprinting. Med Sci Sports Exerc. 2012;44(4):647-658.

41. Seynnes OR, de Boer M, Narici MV. Early skeletal muscle hypertrophy and architectural changes in response to high-intensity resistance training. J Appl Physiol. 2007;102(1):368-373.

42. Sugiura Y, Saito T, Sakuraba K, Sakuma K, Suzuki E. Strength deficits identified with concentric action of the hip extensors and eccentric action of the hamstrings predispose to hamstring injury in elite sprinters. J Orthop Sports Phys Ther. 2008;38(8):457-464.

43. Timpka T, Alonso JM, Jacobsson J, et al. Injury and illness definitions and data collection procedures for use in epidemiological studies in Athletics (track and field): Consensus statement. Br J Sports Med. 2014;48(7):483-490.

44. Tomberlin JP, Basford JR, Schwen EE, et al. Comparative study of isokinetic eccentric and concentric quadriceps training. J Orthop Sports Phys Ther. 1991;14(1):31-36.

45. Witvrouw E, Danneels L, Asselman P, D'Have T, Cambier D. Muscle flexibility as a risk factor for developing muscle injuries in male professional soccer players. A prospective study. Am J Sports Med. 2003;31(1):41-46.

46. Yamamoto T. Relationship between hamstring strains and leg muscle strength. A follow-up study of collegiate track and field athletes. J Sports Med Phys Fitness. 1993;33(2):194-199.

47. Yeung SS, Suen AM, Yeung EW. A prospective cohort study of hamstring injuries in competitive sprinters: preseason muscle imbalance as a possible risk factor. Br J Sports Med. 2009;43(8):589-594.

48. Zakas A. Bilateral isokinetic peak torque of quadriceps and hamstring muscles in professional soccer players with dominance on one or both two sides. J Sports Med Phys Fitness. 2006;46(1):28-35.