Title:

An evidence-based framework for strengthening exercises to prevent hamstring injury.

Running Title: Strengthening exercises to prevent hamstring injury.

Authors:

Matthew N. Bourne[1], Ryan G. Timmins[2], David A. Opar[2], Tania Pizzari[1], Joshua D. Ruddy[2], Casey Sims[3], Morgan D. Williams[4], Anthony J. Shield[3].

[1]Department of Rehabilitation, Nutrition and Sport, La Trobe Sport and Exercise Medicine Research Centre, Melbourne, Australia.

2 School of Exercise Science, Australian Catholic University, Melbourne, Australia.

[3] School of Exercise and Nutrition Science, Faculty of Health, Queensland University of Technology, Brisbane, Australia.

[4]School of Health, Sport and Professional Practice, Faculty of Life Sciences and Education, University of South Wales, Wales, United Kingdom.

Corresponding Author:

Dr Matthew Bourne

Department of Rehabilitation, Nutrition and Sport,
La Trobe Sport and Exercise Medicine Research Centre,
Melbourne, Australia
Email: matthewbourne88@gmail.com
Ph: +61 8 9479 5700

Abstract

Strength training is a valuable component of hamstring strain injury prevention programmes. However, in recent years a significant body of work has emerged to suggest that the acute responses and chronic adaptations to training with different exercises are heterogeneous. Unfortunately, these research findings do not appear to have uniformly influenced clinical guidelines for exercise selection in hamstring injury prevention or rehabilitation programmes. The purpose of this review is to provide the practitioner with an evidence-base from which to prescribe strengthening exercises to mitigate the risk of hamstring injury. Several studies have established that eccentric knee flexor conditioning reduces the risk of hamstring strain when compliance is adequate. The benefits of this type of training are likely to be at least partly mediated by increases in biceps femoris long head fascicle length and improvements in eccentric knee flexor strength. Therefore, selecting exercises with a proven benefit on these variables should form the basis of effective injury prevention protocols. In addition, a growing body of work suggests that the patterns of hamstring muscle activation diverge significantly between different exercises. Typically, relatively higher levels of biceps femoris long head and semimembranosus activity have been observed during hip-extension oriented movements whereas preferential semitendinosus and biceps femoris short head activation have been reported during knee-flexion oriented movements. These findings may have implications for targeting specific muscles in injury prevention programmes. An evidence-based approach to strength training for the prevention of hamstring strain injury should consider the impact of exercise selection on muscle activation, and the effect of training interventions on hamstring muscle architecture, morphology and function. Most importantly, practitioners should consider the effect of a strength training programme on known or proposed risk factors for hamstring injury.

Key Points:

- A number of prospective studies have established that eccentric knee flexor conditioning reduces the risk of hamstring strain injury when compliance is adequate. These benefits are likely to be at least partly mediated by increases in biceps femoris long head fascicle length, possibly a rightward shift in the angle of peak knee flexor torque, and improvements in eccentric knee flexor strength, although other adaptations may also contribute
- A large body of evidence suggests that the acute responses and chronic adaptations to training with different hamstring exercises are heterogeneous. Muscle activation may be an important determinant of training-induced hypertrophy, however, contraction mode appears to be the largest driver of architectural changes within the hamstrings.

1. Introduction

Hamstring strain injury is the most common cause of lost training and playing time in running-based sports[1]. In professional soccer, for example, roughly 1 in 5 players will suffer a hamstring injury in any given season [2], and upwards of 20% of these will re-occur [3]. Each injury will typically result in ~17 days lost from training and competition [2], which not only diminishes performance [4], but is also estimated to cost elite soccer clubs as much as ~€280 000 per injury [5].

It has been argued that most hamstring strains occur during the late swing phase of high speed running and approximately 4 in every 5 affect the long head of biceps femoris [6-8]. While the aetiology of hamstring injury is multifactorial, hamstring strengthening is an important component of injury prevention practices [9-11] and one that has been the focus of a significant amount of research in recent years [12-17]. Large-scale interventions employing the Nordic hamstring exercise have reported 50-70% reductions in hamstring injuries in sub-elite soccer when athletes are compliant [12, 15-17]. Furthermore, hamstring rehabilitation protocols employing long length exercises have proven significantly more effective than conventional exercises in accelerating time to return to play from injury [13, 14]. However, despite these observations, compliance with evidence-based injury prevention protocols is poor [18] and longitudinal data [2, 19-22] suggest that hamstring injury rates have not declined over the past decade in elite soccer and Australian Football. These data highlight the need to improve hamstring injury prevention or risk mitigation practices.

In recent years, a growing body of work has emerged highlighting the heterogeneity of hamstring activation patterns in different tasks [23-28] and the non-uniformity of muscle adaptations to different exercises [29-31]. However, this research does not appear to have influenced clinical guidelines for exercise selection in hamstring injury prevention [32, 33] or rehabilitation programmes [34, 35]. An improved understanding of this empirical work may enable practitioners to make better informed decisions regarding exercise selection for the prevention or treatment of hamstring injury. Therefore, the purpose of this review is to provide an evidence based framework for strengthening exercises to prevent hamstring strain injury. The review will aim to discuss 1) the role of strength as a risk factor for hamstring injury; 2) the evidence for strengthening interventions in the prevention or rehabilitation of hamstring injury; 3) the acute patterns of hamstring muscle activation in different exercises; and 4) the malleability of hamstring muscle architecture, morphology and function to targeted strength training interventions. The review will conclude by discussing the implications of this evidence for hamstring injury prevention practices, with particular emphasis on the impact of these variables on known or proposed risk factors for hamstring injury.

2. Literature search

The articles included in this review were obtained via searches of Scopus and PubMed from database inception to May 2017 (see Electronic Supplementary Material Appendix S1 for search keywords). A retrospective, citation-based methodology was applied to identify English language literature relating to 1) strength as a risk factor for hamstring injury; 2) the outcomes of prospective strength training interventions on hamstring injury rates; 3) hamstring muscle activation during strengthening exercise(s) in individuals with no history of injury; and 4) the structural or functional adaptations to a period of hamstring strength training. Full text journal publications were the primary source, however published conference abstracts and theses were also included if they satisfied the search criteria.

3. Strength as risk factor for hamstring injury

Strength training for the prevention of hamstring injury has been popularised on the basis of the long-held assumption that stronger muscles are more resistant to strain injury [36]. While this may be intuitively appealing, particularly when considering that weakly activated rabbit muscles absorb less energy before failure than fully activated muscles [37], evidence from prospective studies is mixed [38-46]. Although the majority of these studies employed isokinetic dynamometry as their chosen testing methodology [38, 40, 42, 46, 47], more recent field-based measures of eccentric knee flexor strength have also proven reliable [48] and have indicated a level of risk associated with poor eccentric strength [43, 44, 48].

3.1 Isokinetic dynamometry

In the largest isokinetic investigation, involving 190 hamstring injuries in 614 elite Qatari soccer players, van Dyk and colleagues [42] reported that lower levels of eccentric knee flexor strength significantly elevated the risk of future hamstring injury (odds ratio = 1.37; 95% CI, 1.01 to1.85), albeit with a small effect size (Cohen's $d < 0.2$). In contrast, earlier work by Croisier and colleagues [46] which included 35 injuries in 462 Belgian, Brazilian and French professional soccer players, suggested that athletes with isokinetically derived 'strength imbalances' were 5-fold (relative risk 95% CI = 2.01 to 10.8) more likely to suffer severe (>30 days lost) injuries than those without imbalances. In this study [46], correcting these isokinetic parameters via strength training reduced the risk of hamstring injury to the same level as those players without imbalances (relative risk = 1.43; 95% CI = 0.44 to 4.71). However, the results from Croisier and colleagues should be interpreted with caution; firstly, isokinetic testing was conducted at a number of different sites, using different equipment and various arbitrary cut-points, which may have confounded results. Further, the median time to return to sport from hamstring strain is typically less than 30 days [6-8], so it is likely that players in the control group of this study also experienced a significant number of less severe injuries, and this was not accounted for in the analysis. Nevertheless, in a separate study, involving 57 hamstring injuries in 136 professional soccer players, Dauty and colleagues [49] reported that the same isokinetic ‘strength imbalances’ used by Croisier and colleagues, were able to predict approximately 1 in 3 hamstring injuries in the following season and the predictive ability of this testing improved when athletes had multiple imbalances. Fousekis and colleagues [40] have also provided data to suggest that between-limb imbalances in isokinetic eccentric knee flexor torque ≥15% increased the risk of hamstring injury 4-fold (95% CI = 1.13 to 13.23) in elite soccer players. Further, in a prospective investigation involving 6 hamstring injuries in 30 elite Japanese sprinters, Sugiura and colleagues [41] observed that subsequently injured limbs displayed significant deficits in eccentric knee flexor (95% CI = 0.04 to 0.37 Nm/kg) and concentric hip extensor (95% CI = 0.19 to 0.50 Nm/kg) strength when tested in the preceding 12 months. In addition, in a small study involving 6 hamstring injuries in 20 elite Australian Football players, Cameron and colleagues [50] observed that a concentric hamstring to quadriceps ratio of < 0.66 significantly increased the risk of hamstring strain over the following 2 years. Lastly, in a prospective study of 6 injuries in 37 elite Australian Football players, Orchard and colleagues [51] observed that subsequently injured limbs displayed significantly lower concentric isokinetic knee flexor strength than uninjured limbs when tested during the pre-season period.

Despite the aforementioned observations, some studies have failed to identify any association between isokinetic knee flexor strength and hamstring injury risk. In an investigation by Bennell and colleagues [38], involving 9 injuries in 102 elite Australian Football players, no relationship was observed between concentric or eccentric isokinetic knee flexor strength and the likelihood of hamstring injury. However, this study [38] was underpowered to detect small to moderate effects between subsequently injured and uninjured athletes, such as those identified by van Dyk and colleagues [42]. A larger-scale investigation involving 1252 collegiate athletes at the National Football League Scouting Combine observed that isokinetically-derived measures of concentric knee flexor strength were not associated with hamstring injury risk in the following competitive season [52]. However, like Croisier and colleague's earlier investigation [46], this study did not employ a standardised testing procedure and strength testing was conducted by different practitioners across a number of sites; therefore it is unclear what effect this may have had on the reliability of these different datasets.

3.2 Field-based measures

Field-based measures of eccentric knee flexor strength may also be effective for identifying athletes at risk of a future hamstring strain [43, 44]. In a prospective investigation involving 28 injuries in 210 Australian Football players, those with lower levels of eccentric knee flexor strength (<279 N) during the Nordic hamstring exercise were 4.3 times (relative risk 95% CI = 1.7 to 11.0) more likely to suffer a hamstring injury in the following season than their stronger counterparts [43]. These findings were supported in a subsequent study [44] involving 27 hamstring injuries in 152 professional soccer players, which reported that athletes with lower levels of eccentric knee flexor strength (<337 N) were 4.4 times (relative risk 95% CI = 1.1 to 17.5) more likely to sustain a hamstring injury than stronger athletes. In both of these investigations [43, 44], a 10 N increase in strength across the sampled athletes was associated with a 9% smaller risk of future hamstring strain injury. It should also be acknowledged that interactions were observed between eccentric knee flexor strength, age and previous hamstring injury, whereby higher levels of eccentric strength were able to ameliorate the risk of injury associated with being older or having a history of hamstring injury. Nevertheless, a similarly designed study, involving 20 hamstring injuries in 198 amateur and professional rugby players [45], failed to identify an association between eccentric knee flexor strength and hamstring injury. However, in this study, side-to-side imbalances in eccentric strength of ≥15% and ≥20% increased the risk of hamstring injury by 2.4-fold (95% CI = 1.1 to5.5) and 3.4-fold (95 % CI = 1.5 to 7.6), respectively. Lastly, in a prospective investigation involving 8 first-time hamstring injuries in 102 physical education students [53], lower levels of absolute eccentric hamstring strength and a higher isometric to eccentric strength ratio, as measured via hand-held dynamometry, significantly elevated the risk of subsequent hamstring strain.

4. Does strength training protect against hamstring strain injury and re-injury?

Over the past decade, a number of prospective studies have established that strength training, particularly when performed with an eccentric bias or at long muscle lengths, reduces the risk of hamstring injury, as long as compliance is high [12-17]. In the first of these studies, Askling and colleagues [54] administered a 10 week YoYo flywheel (a leg curl device which provides eccentric overload) training programme to 15 (from a total pool of 30) elite Swedish soccer players. Across the subsequent season, players in the intervention group experienced significantly fewer (3/15) hamstring strains than those in the control group (10/15). A number of subsequent randomised controlled trials employing the Nordic hamstring exercise have also reported benefits from eccentric conditioning, but only when compliance is adequate [12, 15-17] In the largest of these studies, Petersen and colleagues [15] assigned a 10 week Nordic hamstring programme [55] to 461 of 942 sub-elite Danish soccer players who were subsequently tracked for injury across a single season. Players in the intervention group experienced 71% fewer first-time and 85% fewer recurrent hamstring injuries than players in the control group. However, it should be noted that athletes in this study [55] had no known history of strength training. More recent work by van der Horst and colleagues [17] allocated 292 of 597 sub-elite Dutch soccer players to a similar 13 week Nordic hamstring strengthening programme and reported that players who completed the training experienced 69% fewer hamstring strains that those who did not (odds ratio = 0.3, 95% CI = 0.1 to 0.7). Furthermore, Arnason and colleagues [12] reported that Icelandic and Norwegian soccer teams that completed a progressive intensity Nordic exercise programme in pre-season (and a lower volume of the exercise during the competitive season), experienced 65% fewer hamstring strains than those that did not (relative risk = 0.35, 95% CI = 0.2 to 0.6). One limitation of these Scandinavian studies is that they only involved amateur soccer players and consequently it might be argued that they are not applicable to more elite levels of competition. However, in a non-randomised trial, Seagrave and colleagues [16] have recently shown that among 243 professional baseball players from a single Major League baseball organisation, those who completed the Nordic hamstring exercise as a part of their team training did not suffer a single hamstring injury throughout the season. In contrast, 9% of athletes who did not complete the exercise missed matches due to hamstring injury.

It should be acknowledged that two prospective studies employing the Nordic hamstring exercise, both with very low rates of player compliance, have found no significant effect on hamstring injury rates [47, 56]. In the first of these studies, Engebretsen and colleagues [56] allocated 85 of 161 elite to sub-elite Norwegian soccer players at ‘high risk’ of hamstring injury to a 10-week Nordic hamstring protocol [55] and reported no benefit of this intervention on injury rates (relative risk = 1.6; 95% CI = 0.8 to 2.9); however, only 1 in 5 players in the intervention group completed the programme [56]. In a subsequent study by Gabbe and colleagues [47], 114 of 220 amateur Australian Football players were asked to complete 5 high volume sessions (~72 repetitions each) of the Nordic hamstring exercise across a 12 week period. This study also reported no benefit of eccentric conditioning on hamstring injury risk (relative risk = 1.2, 95% CI = 0.5 to 2.8); however, only 47% of players completed two training sessions and < 10% completed all five. Those players in the intervention who participated in at least the first two sessions suffered fewer injuries than the control group (4% versus 13%) but this small effect was not statistically significant (relative risk = 0.3, 95% CI = 0.1 to 1.4).

Rehabilitation studies employing strengthening exercises at long hamstring muscle lengths have also proven effective in reducing re-injury rates and accelerating time to return to sport [13, 14]. In two separate randomised controlled trials, Askling and colleagues compared a rehabilitation protocol (‘L’ protocol) emphasising long length hip extension-oriented movements (extender, glider, diver) to a conventional (‘C’ protocol group) consisting of a contract-relax stretch, a supine bridge and cable pulley exercise performed at shorter hamstring lengths. Elite track and field athletes [13] and professional soccer players [14] who completed the L-protocol experienced a faster return to sport (mean = 28-49 days versus 51-86 days) and no injury recurrences compared to the C-protocol that experienced three. More recently, Tyler and colleagues [57] reported that a progressive criteria-based rehabilitation protocol emphasising eccentric exercises at long hamstring muscle lengths was particularly effective in reducing injury recurrence. Of the 50 athletes who enrolled in the study, those who completed the structured strengthening programme and met return to sport criteria (n=42) remained injury free 23±13 months after a return to sport, whereas 4 athletes who were non-compliant with the exercise programme suffered a re-injury in the following 3-12 months [57].

The aforementioned findings provide compelling evidence for the protective role of eccentric only or eccentrically biased strength training against first time and recurrent hamstring injury, but only when compliance is adequate [12-17, 57]. However, most of these studies only explored the injury preventive benefits of a single exercise [12, 15-17, 54] in individuals with no history or unknown histories of strength training, which has limited application to sporting or clinical environments where a combination of exercises are typically employed. An improved understanding of the acute responses and chronic adaptations to various exercises may enable clinicians to make better informed decisions when designing strengthening programmes for the prevention of hamstring injury.

5. Impact of exercise selection on hamstring muscle activation

Skeletal muscle activation has the potential to influence the functional and structural adaptations to resistance training [29, 58, 59] and there is a growing body of work to suggest that the hamstrings are activated heterogeneously during a range of different exercises [24-28, 60, 61]. Most of these studies have employed either surface electromyography (sEMG) or functional magnetic resonance imaging (fMRI) to map the acute electrical or metabolic activity of the hamstrings during different tasks. The purpose of this section is to provide an overview of the techniques that have been used to assess hamstring activation, highlight the key methodological considerations when interpreting these data, and summarise the available evidence as it relates to the impact of exercise selection on hamstring muscle activation.

5.1. Methods for assessing hamstring muscle activation

5.1.1. Surface electromyography (sEMG)

Surface EMG has been used extensively in the analysis of hamstring exercises [27, 28, 60, 61]. This method utilises electrodes, which are placed on the skin overlying the target muscle, to measure the electrical activity generated by active motor units. The EMG amplitude recorded during an exercise is typically expressed relative to the highest level of activation achieved during a maximal voluntary contraction (MVC) [62]. This provides an estimate of voluntary activation (which includes both motor unit recruitment and firing rates) for assessed muscles involved during exercise, with high temporal resolution. However, the coefficient of variation for repeated sEMG measurements has been reported to be as high as 23% [63]. One major limitation of sEMG is its susceptibility to cross talk from neighbouring muscles [62]. As a consequence, it is not possible to reliably discriminate between closely approximated muscles or segments of muscles [64] such as the long and short heads of biceps femoris or either of the medial hamstrings (semimembranosus and semitendinosus) [23]. Surface EMG amplitude is also influenced by the amount of subcutaneous tissue [62], motor unit conduction velocities [65], and the degree to which motor unit firing is synchronous [66]. Furthermore, interpretation of EMG studies is often confounded by inconsistent testing procedures. For example, it is rare to find two studies that have employed the same normalisation technique, and electrode placement is rarely described in adequate detail. Furthermore, some studies differentiate EMG amplitudes between contraction modes [23, 27], whereas others do not [60, 67], which makes comparison difficult (i.e., concentric actions produce higher EMG than eccentric actions at the same load [62]). Nevertheless, appropriately designed and methodologically vigorous studies that minimise the aforementioned limitations can yield valuable information on the extent and patterns of muscle activation during various exercises.

5.1.2. Functional magnetic resonance imaging (fMRI)

The use of fMRI to estimate muscle activation in exercise has become increasingly popular [23-28] since first described by Fleckenstein in 1988 [68]. This technique is based on the premise that muscle activation is associated with a transient increase in the transverse (T2) relaxation time of tissue water, which can be measured from signal intensity changes in fMRI images. These T2 shifts, which increase in proportion to exercise intensity [68, 69], can be mapped in cross-sectional images of muscles and therefore provide exceptional spatial clarity [64, 70]. However, because acute T2 shifts are sensitive to glycolysis [71], and concentric work is markedly less efficient than eccentric work against the same loads [72], it is not sensible to compare the magnitude of T2 shifts between contraction modes, although this has been done previously [73]. Similarly, the extent to which T2 relaxation time increases during exercise can be influenced by muscle fibre composition, metabolic capacity [74] and the vascular dynamics of the active tissue [75], and these factors are likely to differ between individuals. It is therefore inappropriate to compare the absolute magnitude of T2 shifts between individuals because a larger increase in T2 for one subject over another cannot be interpreted as more effective activation. Instead, analytical techniques that compare relative changes in T2 within individuals appear most appropriate and can provide important information on the patterns of muscle use employed in different tasks.

5.1.3 Factors to consider when interpreting sEMG and fMRI

Given the methodological complexities of sEMG and fMRI, there are some additional factors that should be considered when interpreting data from these studies. Firstly, because both EMG [62] and T2 relaxation times [69] increase in proportion to exercise intensity, greater loads will typically result in higher levels of ‘activation’ than lower loads for any given exercise. Therefore, when comparing different exercises it is important to consider the relative intensity of each task. In addition, when comparing the ‘patterns’ of muscle activation between exercises it is important to consider that the ratio of lateral to medial (or biceps femoris long head to semitendinosus) ‘activation’ is calculated independently of the magnitude of sEMG or T2 relaxation time increase. It is possible that some exercises may elicit selective activation of a desired structure, but the extent of activation may still be insufficient to stimulate positive adaptations.

5.2. Hamstring muscle activation during specific exercises

5.2.1. Magnitude of hamstring muscle activation

Studies employing sEMG have shown that the magnitude of hamstring muscle activation is variable between exercises. During eccentric-only movements, very high levels of biceps femoris (72-91% MVC) and medial hamstring normalised EMG (nEMG) (82-102% MVC) have consistently been observed during the Nordic hamstring exercise [23, 60, 76]. Most other studies have not differentiated between contraction modes and instead report mean values across the entire movement. Very high levels of biceps femoris and medial hamstring nEMG (>80% MVC) have been reported for supine sliding bodyweight leg curls [60, 67], seated and prone leg curls [60, 77], loaded and unloaded hip extension [60], kettlebell swings [60], and a supine straight leg bridge [23, 60, 67].

5.2.2. Patterns of hamstring muscle activation

Several sEMG studies have attempted to characterise the patterns of individual hamstring muscle activation during different strengthening exercises. A recent study [23] reported more selective biceps femoris nEMG activity in eccentric and concentric actions during the 45^0 hip extension and hip hinge exercises. In contrast, the same study observed more selective nEMG of the medial hamstrings during an eccentric and concentric leg curl and the Nordic hamstring exercise, despite the latter demonstrating the highest absolute levels of biceps femoris nEMG of any exercise. This is in line with earlier work by Ono and colleagues [28] who observed more selective nEMG of the biceps femoris and semimembranosus relative to the semitendinosus during the eccentric and concentric phases of a stiff leg deadlift. In contrast, during a supramaximal eccentric-only leg curl, the same authors [27] observed with sEMG that the semitendinosus was significantly more active than the semimembranosus and trended towards being more active than the biceps femoris. In support of these findings, McAllister and colleagues [78] reported significantly more biceps femoris nEMG during an eccentric Romanian deadlift than an eccentric prone leg curl and eccentric glute-ham-raise, and significantly more biceps femoris nEMG during an eccentric good morning squat than a prone leg curl. However, other authors have found conflicting results. For example, Zebis and colleagues [60] observed higher levels of semitendinosus than biceps femoris nEMG during a kettlebell swing and Romanian deadlift, and higher levels of biceps femoris than semitendinosus nEMG during a supine leg curl and hip extension exercise. Furthermore, Tsaklis and colleagues [67] observed preferential recruitment of the biceps femoris during ‘fitball’ flexion, and selective nEMG activity of the semitendinosus during a lunge, kettlebell swing and single leg Romanian deadlift. However, these two previous studies [60, 67] did not report sEMG for each contraction mode, which may at least partly explain the divergent results.

Studies using fMRI are generally consistent with the results of sEMG investigations; however, the increased spatial clarity of this technique allows for inferences to be drawn on the relative metabolic activity of each hamstring muscle belly (Figure 1). Early work by Ono and colleagues [27] revealed that the semitendinosus is selectively activated during the eccentric prone leg curl, while the semimembranosus and biceps femoris are preferentially recruited during the stiff leg deadlift [28]. More recent observations have provided evidence that the semitendinosus is preferentially recruited during the Nordic hamstring exercise [23, 24, 26, 73, 79], and a prone leg curl [25]. In contrast, the biceps femoris long head and other biarticular hamstrings appear to be more active during a 45^0 hip extension exercise than the Nordic exercise [23]. In addition, the long head of biceps femoris appears to be significantly more active than its short head during a single leg supine bridge exercise [80]. Further, Mendiguchia and colleagues have observed elevated T2 values in the proximal but not middle or distal portions of biceps femoris long head after a lunge exercise [25]. Figure 1 illustrates the ratio of biceps femoris long head to semitendinosus activity (as determined via exercise-induced T2 relaxation time shifts) during all studies that have reported these data. Ratios > 1.0 indicate higher levels of biceps femoris long head than semitendinosus activity.

INSERT FIGURE 1

Figure 1. Ratio of BFLH to ST percentage change in T2 relaxation time from different exercises. Ratios > 1.0 indicate higher levels of BFLH than ST activity. Note the trend for relatively higher levels of BFLH activity during hip extension-oriented movements and more selective ST activity during knee flexion-oriented movements. BFLH, biceps femoris long head; BW, bodyweight; RM, repetition maximum; ST, semitendinosus; T2, transverse relaxation time.

Collectively, the abovementioned findings suggest that the magnitude and patterns of muscle activation are heterogeneous between different exercises. While the results of sEMG investigations are variable, the improved spatial clarity of fMRI suggests that knee flexion-oriented movements (i.e., Nordic hamstring exercise, leg curl) appear to selectively activate the semitendinosus, whereas movements involving a significant amount of hip extension (i.e., stiff leg deadlift) appear to more heavily activate the biceps femoris long head and semimembranosus (Figure 1). Importantly, these patterns of preferential activation have recently been shown to match the patterns of hamstring muscle hypertrophy after 10 weeks of training [29], as discussed in section 6.2.

5.3. Hamstring muscle damage following specific exercises

In addition to the acute T2 response to exercise, unaccustomed eccentric exercise can be associated with a delayed T2 increase which parallels indices of muscle damage [70]. This prolonged T2 increase is thought to arise as a consequence of oedema [81], and can therefore persist for days to weeks after exposure to unaccustomed exercise involving eccentric muscle actions [82]. In one of the few studies to have assessed this parameter in the hamstrings, Kubota and colleagues [83] demonstrated that 50 repetitions of an eccentric leg curl exercise performed at 120% 1-repetition maximum (1RM) resulted in an elevated T2 value for the semitendinosus, but not the biceps femoris long head or semimembranosus, 72 hours after exercise. Similar results were reported by Mendiguchia and colleagues [25] who observed an increased T2 value for the semitendinosus, but not the biceps femoris or semimembranosus, 48 hours after 18 repetitions of an eccentric leg curl exercise. Subsequent work [26] reported that 40 repetitions of the supramaximal Nordic hamstring exercise resulted in an elevated T2 value for the distal portion of biceps femoris short head for up to 72 hours after exercise; however, no changes were observed for any of the other hamstrings. Lastly, Ono and colleagues [28] observed a significant increase in T2 for the semimembranosus 72 hours after 50 repetitions of submaximal (60% 1RM) hip extension exercise. Collectively, these observations suggest that unaccustomed eccentrically biased exercise is likely to result in some damage to the trained muscles particularly when the intensity is supramaximal (i.e., ≥1RM loads), and the distribution of that damage appears to be closely related to the acute T2 shifts observed immediately after exercise (Figure 1). These findings may have implications for the structural adaptations experienced from training, which should be a focus of future work.

6. Architectural, morphological and performance-based adaptations to different exercises

The adaptability of hamstring structure and function in response to various training interventions may have important implications for strategies aimed at preventing hamstring injury. It is particularly relevant to consider the effect of various exercises on known or proposed risk factors for hamstring strain injury, such as biceps femoris long head fascicle length [44] and eccentric knee flexor strength [42-44, 46]. This section aims to describe the results of training studies that have explored the architectural, morphological or functional adaptations to a period of hamstring conditioning, while also providing a rationale for why certain adaptations are considered favourable in the context of mitigating the risk of hamstring injury.

6.1. Biceps femoris long head fascicle length

Recent evidence suggests that professional soccer players with shorter biceps femoris long head fascicles (<10.56cm) were 4.1-times more likely to sustain a future hamstring strain injury than those with longer fascicles and that the probability of injury was reduced by ~21% for every 1cm increase in fascicle length (Figure 2) [44]. Retrospective evidence also suggests that previously injured biceps femoris long head muscles display significantly shorter fascicles than muscles without a history of injury [84]. While the mechanism(s) by which shorter fascicles predispose an individual to strain injury is not fully understood, it is hypothesised that shorter fascicles, with fewer sarcomeres in series, will be more susceptible to damage as a consequence of sarcomere “popping”, while actively lengthening on the descending limb of the force-length curve [85]. Therefore, fascicle lengthening is thought to be at least partly mediated by the addition of in-series sarcomeres which would serve to reduce the over-lengthening of those sarcomeres during subsequent eccentric exercise [86].

INSERT FIGURE 2

Figure 2. Pre-season biceps femoris long head fascicle length (y axis) and eccentric knee flexor (Nordic) strength (x axis) values for professional soccer players who did (red dots) and did not (green dots) suffer a hamstring strain injury in the subsequent competitive season. Dotted lines

indicate receiver-operator curve derived cut points for each variable; players with short biceps femoris long head fascicles (< 10.56cm) and low eccentric strength (< 337 N) were 4.1 and 4.4 times, respectively, more likely to suffer a future hamstring strain injury than those with longer fascicles or higher levels of strength [44].

Biceps femoris long head fascicle length has been shown to increase following eccentric but not concentrically biased resistance training (Table 1). Potier and colleagues [31] observed a 34% increase in biceps femoris long head fascicle length following 8 weeks of eccentric leg curl exercise. Further, Timmins and colleagues [30] reported a 16% increase in biceps femoris long head fascicle length after 6 weeks of eccentric training on an isokinetic dynamometer. In the same study, the authors also noted that long length concentric training on the same device resulted in a 12% reduction in biceps femoris long head fascicle length [30] Similarly, concentric only leg curl training has been reported to result in a 6% shortening of biceps femoris long head fascicles [87]. In contrast, both low [88, 89] and high volume [29, 88, 90, 91] programmes employing the eccentric-only Nordic hamstring exercise observed a 13-24% increase in biceps femoris long head fascicle length across a 4-10 week training period (Figure 3). Furthermore, 10 weeks of conventional (combined eccentric and concentric contractions) hip extension training at long hamstring lengths resulted in a 13% increase in biceps femoris fascicle length (Figure 3) [29]. Lastly, Guex and colleagues [92] observed a 5% and 9% increase in biceps femoris long head fascicle length after short-length and long-length eccentric training on an isokinetic dynamometer. Only two studies have failed to observe an increase in biceps femoris fascicle length following a period of eccentric conditioning [91, 93]; however, in one of these studies [91], training was performed in a fatigued state and in the other [93] the authors also noted no improvement in eccentric knee flexor strength. These observations suggest the possibility that the intensity of exercise in each of these interventions may not have been sufficiently high to stimulate sarcomerogenesis. Together, these data suggest that concentric and eccentric actions appear to have opposing effects on hamstring architecture and that the combination of contraction modes (as observed in almost every conventional strength training exercise) may somewhat dampen the elongation of biceps femoris long head fascicles.

Table 1. Strength training interventions studies that have reported architectural changes to the biceps femoris long head.

Study	**Exercise**	**Contraction mode(s)**	**Peak MTU length**	**Intensity**	**Maximum volume (sets*reps / session)**	**Maximum frequency (sessions / week)**	**Biceps femoris long head fascicle length**
Presland et al. [88]	Nordic Nordic	Eccentric Eccentric	Moderate Moderate	Supramax Supramax	5*10 4*2	2 2	+ 23% + 24%
Duhig et al. [87]	Nordic Leg curl	Eccentric Concentric	Moderate Moderate	Supramax 6-8RM	5*6 5*6	2 2	+ 13% - 6%
Lovell et al. [91]	Nordic (*bef*) Nordic (*aft*) Static & side bridge	Eccentric Eccentric Isometric	Moderate Moderate Short	Supramax Supramax Isometric	4*12 4*12 3*40sec	2 2 2	+ 12.9% - 2.3% - 5.4%
Alvares et al. [89]	Nordic	Eccentric	Moderate	Supramax	3*10	2	+ 22%
Alonso-Fernandez et al. [90]	Nordic	Eccentric	Moderate	Supramax	3*10	3	+ 23.9%
Seymore et al. [93]	Nordic	Eccentric	Moderate	Supramax	3*8-12	3	+ 0.0%
Bourne et al. [29]	Nordic Hip extension	Eccentric Conventional	Moderate Long	Supramax 6-10RM	5*10 5*10	2 2	+ 21% + 13.2%
Timmins et al. [30]	Seated isokinetic knee flexion	Eccentric Concentric	Long Long	Maximal Maximal	6*8 6*8	3 3	+ 16% - 11.8%
Guex et al.[92]	Seated isokinetic knee flexion Lying isokinetic knee flexion	Eccentric Eccentric	Long Short	Maximal Maximal	5*8 5*8	3 3	+ 9.3% + 4.9%
Potier et al. [31]	Leg curl	Eccentric	Moderate	1RM	3*8	3	+ 34%

MTU, muscle-tendon unit; Supramax, supramaximal; RM, repetition-maximum; *bef*, performed before regular training; *aft*, performed after regular training.

INSERT FIGURE 3

Figure 3. Training-induced increases in biceps femoris long head fascicle length (y axis) and eccentric knee flexor (Nordic) strength (x axis) following 6-10 weeks of hip extension training (red dots), or high (blue and green dots) and low volume (purple dots) Nordic hamstring training [29, 88]. The size of each data point indicates the estimated probability of future hamstring strain, based on previously published data in elite soccer players (Figure 2) [44]. Note, all individuals experience a reduction in hamstring injury risk as a consequence of the training intervention. HSI, hamstring strain injury.

6.2 Myotendinous junction

Recently, it has been proposed that a small proximal biceps femoris long head aponeurosis may be a risk factor for future hamstring strain injury [94]. Although prospective investigations are lacking, computational modelling [95, 96] has demonstrated that biceps femoris aponeurosis geometry has a significant impact on the location and magnitude of strain within this muscle. For example, Rehorn and colleagues [96] reported that an 80% reduction in the width of the proximal biceps femoris long head aponeurosis increased proximal myotendinous junction (MTJ) strains by 60%. Given that running-induced strain injury occurs most commonly at the proximal MTJ of the biceps femoris long head [97], it is plausible that interventions targeted at improving the size of the proximal aponeurosis may confer some injury preventive benefits. Despite this possibility, the authors are not aware of any study to explore training-induced adaptations to the size of this structure. However, Wakahara and colleagues [98] have recently reported that training-induced hypertrophy of the vastus lateralis was correlated with an increase in the width of this muscle's aponeurosis (r=0.64), and others have previously shown that weightlifters display larger vastus lateralis aponeuroses than untrained individuals [99]. These data suggest the possibility that aponeurosis geometry may increase as a function of muscle hypertrophy; however, further work is required to confirm this hypothesis.

In light of evidence that strain magnitudes are greatest in the proximal MTJ of the hamstrings, the composition of this structure and its surrounding fibres is another factor which could, theoretically, influence its susceptibility to damage. Jakobsen and colleagues [100] have recently shown that 4 weeks of knee-flexor strength training involving the Nordic hamstring exercise, leg curls and hip extensions altered collagen expression in the endomysium of muscle fibres at the MTJ junction of the semitendinosus and gracilis. In particular, the authors noted that training increased the amount of collagen XIV, a protein that may be important in strengthening the extracellular matrix and unloading the MTJ [100]. These results suggest that altered collagen expression may be at least one additional mechanism by which strength training protects against hamstring strain injury, and this should be a focus of subsequent investigations. Future work should also seek to determine the effect of exercise selection, contraction mode and training intensity on these adaptations.

6.3. Hamstring muscle size

Muscle volume has not been identified as a risk factor for hamstring strain injury. However, previously injured hamstrings have been reported to display significant deficits in muscle size as measured via MRI, despite apparently successful rehabilitation and a return to pre-injury levels of training and competition (Figure 4) [101]. Future work is needed to clarify if these deficits lead to an increased risk of injury; however, the associated cost (~ $600 AUD per hour for MRI) and time-demands (~4 hours to analyse a single scan) of these types of studies may be a limiting factor. Nevertheless, muscle strength is directly correlated to its anatomical cross sectional area [102], and it therefore seems logical that hypertrophy should be a goal of interventions aimed at improving hamstring strength.

INSERT FIGURE 4

Figure 4. Unpublished observations of biceps femoris long head atrophy and compensatory hypertrophy of its short head 4.5 years following a distal biceps femoris strain injury in a national champion long jump athlete. These data are consistent with earlier findings by Silder and colleagues [101].

To the authors’ knowledge, only two studies have explored the hypertrophic adaptations of the hamstrings to strength training. In the first [29], MRI was used to measure hamstring muscle volumes and peak anatomical cross-sectional areas before and after a period of hamstring conditioning. Following 10 weeks of training, hip extension exercise resulted in relatively uniform hypertrophy of the biarticular hamstrings and significantly more growth of the biceps femoris long head than did the Nordic hamstring exercise, which preferentially developed the semitendinosus and the short head of biceps femoris. In a separate investigation, Seymore and colleagues [103] employed panoramic ultrasound to determine the effect of 6 weeks of Nordic hamstring training on biceps femoris long head and semitendinosus volume. In line with the aforementioned MRI observations [29], the semitendinosus experienced twice as much hypertrophy (~20% increase in volume) as the biceps femoris long head (~10% increase in volume). Interestingly, the patterns of muscle hypertrophy experienced by participants in the first of these studies [29] were an almost exact match to the acute T2 changes observed after 50 repetitions of each exercise in a previous study (Figure 5) [23]. These observations match those of earlier work by Wakahara and colleagues [58] who demonstrated that regional differences in triceps brachii activation during elbow extensor exercise, as revealed by fMRI after a single session, predicted regional differences in muscle hypertrophy following 12 weeks of training. This suggests that fMRI studies of the hamstrings may have the potential to identify the exercises that are most effective in stimulating hypertrophic adaptations in the biceps femoris long head (or either of the medial hamstrings), but further work is needed to confirm this hypothesis. It should also be noted that while the Nordic hamstring exercise appears to cause small to moderate acute changes in T2 relaxation times and minimal hypertrophy in the biceps femoris long head, this does not prevent large changes in fascicle lengths from occurring [29].

INSERT FIGURE 5

Figure 5. Previously published observations [23, 29] demonstrating similarities between the acute T2 shifts (grey bars) observed after 50 repetitions of the a) Nordic hamstring exercise, and b) hip extension exercise, and the hypertrophic adaptations experienced after 10 weeks of training (black bars). Adapted from Bourne et al. [23] and Bourne et al. [29], with permission. Data are presented as mean ± SD. BFLH, biceps femoris long head; BFSH biceps femoris short head; ST, semitendinosus; SM, semimembranosus. T2, transverse relaxation time.

In recent years, two-dimensional ultrasound has proven reliable in assessing measures of mid-muscle belly thickness in the biceps femoris long head [84], and a series of underpowered studies have employed it to examine changes in the size of this muscle following training interventions. However, it should be acknowledged that this technique does not currently allow for inferences to be drawn on the ‘patterns’ of muscle hypertrophy within or between the hamstring muscles. In the first of these studies, Timmins and colleagues [30] reported that 6 weeks of concentric or eccentric-only training on an isokinetic dynamometer resulted in non-significant 0.1cm (95% CI = -0.1 to 0.4cm) and 0.2cm (95% CI = -0.1 to 0.5cm) increases in biceps femoris long head thickness, respectively. More recently, Presland and colleagues [88] observed no significant increase in biceps femoris long head thickness after a low (0.1cm, 95% CI = -0.4 to 0.5cm) or high volume (0.1cm, 95% CI = -0.3 to 0.6cm) programme consisting exclusively of the Nordic hamstring exercise. Similarly, Alonso-Fernandez and colleagues [90] noted a ~0.2cm increase in biceps femoris thickness after 9 weeks of Nordic training, while Lovell and colleagues [91] noted a ~0.2cm increase after 12 weeks of training, but only when Nordics were completed in a fatigued state (i.e., after regular soccer training). In contrast, Alvares and colleagues [89] observed no increase in biceps femoris size after 4 weeks of training with the same exercise. Together, these data support the aforementioned MRI [29] and panoramic ultrasound [103] observations in suggesting that the Nordic hamstring exercise may not provide a powerful stimulus for hypertrophy in the biceps femoris long head. However, it is possible that these adaptations may be influenced by the volume of training, or the timing of when that training is completed.

6.4. Knee flexor strength

Higher levels of eccentric but not concentric knee flexor strength have been shown in most [40, 42-44, 46], but not all prospective studies [38, 45], to be associated with a reduced risk of hamstring injury (Figure 2). Therefore, it is of interest to determine the adaptability of eccentric knee flexor strength in response to different training interventions. Askling and colleagues [54] reported a significant 19% increase in isokinetic eccentric knee flexor strength after 10 weeks of eccentric YoYo fly wheel training on a leg curl ergometer. Similarly, Mjolsnes and colleagues [55] reported an 11% increase in eccentric isokinetic knee flexor strength at $-60^{0}.s^{-1}$ after 10 weeks of Nordic hamstring exercise training. In the same study [55], athletes who completed concentrically biased leg curl training experienced no improvement in eccentric strength. More recently, Timmins and colleagues [30] reported a 13-17% increase in eccentric isokinetic knee flexor torque at a range of velocities, following 6 weeks of eccentric or concentric only training on the same device. Furthermore, 10 weeks of Nordic hamstring or hip extension training resulted in a 74% and 78% increase in peak eccentric knee flexor force as measured during the Nordic hamstring exercise (Figure 3) [29]. In comparison, two separate studies have shown that a briefer 4 week period of Nordic hamstring training resulted in a ~14% [89] and ~21% [104] increase in peak eccentric knee flexor torque as measured on an isokinetic dynamometer [89], although a similar study failed to observe any increase in this parameter [93]. Only one study has explored the effect of training volume on eccentric knee flexor strength. In this study, Presland and colleagues [88] observed a 30% and 27.5% increase in eccentric knee flexor strength during the Nordic hamstring exercise following 6 weeks of low (8 repetitions per week) or high (up to 100 repetitions per week) volume training, respectively, on the same device (Figure 3). These data suggest the possibility that very low volumes of intense eccentric knee flexor training may be effective in improving eccentric strength, which may have implications for encouraging compliance with hamstring injury prevention programmes [18, 105].

Some studies have reported improvements in eccentric knee flexor strength following programmes incorporating several exercises. For example, Guex and colleagues [106] observed a 20-22% improvement in eccentric isokinetic strength at $-30^0.s^{-1}$ and $-120^0.s^{-1}$ following 6 weeks of eccentric-only leg curls and hip extension exercises (in conjunction with regular sprint training). Further, Holcomb and colleagues [107] observed a significant improvement in eccentric isokinetic knee flexor strength relative to concentric quadriceps strength following 6 weeks of conventional hamstring conditioning including single leg hamstring curls, stiff leg deadlifts, good morning squats, trunk hyperextensions, resisted sled walking and a ‘fitball leg curls’. More recently, Mendiguchia and colleagues [108] reported a moderate to large improvement in eccentric knee flexor strength (mean = 13%, $d = 0.66$) after 7 weeks of ‘neuromuscular training’ emphasising eccentric (Nordic hamstring and box drops) and conventional (bilateral and unilateral deadlifts, hip thrusts, lunges) hamstring exercises.

6.5. Angle of peak knee flexor torque

A rightward shift in the torque-joint angle relationship of the knee flexors may increase the ability of the hamstrings to generate higher levels of torque at longer muscle lengths. Brockett and colleagues [109] were the first to demonstrate that a single session of 72 repetitions of the Nordic hamstring exercise resulted in a significant ~8° shift in the angle of peak knee flexor torque towards longer muscle lengths for up to 8 days after training. These findings were supported by Clark and colleagues [110] who reported a $\sim6.5^0$ shift after 4 weeks of lower volume Nordic hamstring training, and more recently by Seymore and colleagues [93] who noted a $\sim3.6^0$ shift following 6 weeks of training with the same exercise. Brughelli and colleagues [111] also demonstrated that 4 weeks of Nordic hamstring conditioning stimulated a $\sim2.3^0$ shift in the angle of peak knee flexor torque toward longer muscle lengths in a group of professional soccer players. However, in this study [111], athletes who completed eccentric box drops, lunge pushes, forward deceleration steps and a ‘reverse Nordic’ exercise in addition to regular Nordics experienced a significantly greater shift (4^0) than those who did not. In a separate multimodal intervention, Kilgallon and colleagues [112] reported that 7 sessions of eccentrically-biased leg curls and stiff leg deadlifts resulted in a $\sim20^0$ shift in the angle of peak torque towards a more extended knee angle 4 days after training, while concentrically biased training with the same exercises resulted in a 7^0 shift towards shorter muscle lengths. Lastly, Guex and colleagues [92] observed a 17.3% shift in the angle of peak knee flexor torque toward longer muscle lengths after long length eccentric training on an isokinetic dynamometer, with no significant change noted after short length training on the same device. Collectively, the aforementioned studies suggest that short periods of hamstring conditioning, employing eccentrically biased or long length exercises, stimulate significant increases in the angle of peak knee flexor torque towards longer muscle lengths. The mechanism(s) underpinning these short-lived adaptations is not fully understood, but it is likely that architectural changes (i.e., increased fascicle lengths) in the trained muscles are at least partly responsible [86].

6.6. Performance

Some of the aforementioned studies have also explored the impact of hamstring strength training on measures of performance. For example, in the study by Askling and colleagues [54], a 2.4% improvement in running speed over 30m was reported after 10 weeks of flywheel leg curl training. Furthermore, 7 weeks of hamstring strength training coupled with plyometric and acceleration training resulted in a small (mean = 1.6%, d = 0.3) improvement in 5m but not 20m sprint speed [108]. Lastly, Clark and colleagues [110] noted a significant improvement in vertical jumping height following 8 sessions of Nordic hamstring training.

7. Implications for hamstring injury prevention practices

Despite an increased focus on hamstring strength in prophylactic programs, exercise selection is often implemented on the basis of clinical recommendations and assumptions rather than empirical evidence [32-35]. It is often argued that exercises should mimic the load, range of motion and velocities experienced during the presumably injurious terminal-swing phase of sprinting to be effective in reducing injury [32, 33, 106]. While this type of theoretical framework may be conceptually appealing, it neglects to consider what effect, if any, such exercises may have on previously identified risk factors for hamstring injury. It also ignores the fact that the Nordic hamstring exercise, which fulfils almost none of these criteria, has a uniquely strong evidence base for preventing hamstring strain injury [12, 15-17].

Over the past decade, a number of prospective studies have established that eccentric knee flexor conditioning reduces the risk of hamstring strain injury [12-17]. The benefits of this form of exercise are likely to be mediated at least partly by increases in biceps femoris long head fascicle length [29, 44], possibly a rightward shift in the angle of peak knee flexor torque [110-

112], and improvements in eccentric knee flexor strength (Figure 3) [29, 44]. However, reductions in first-time injuries have only been reported as a consequence of interventions employing the Nordic hamstring exercise [12, 15-17] or an eccentric fly wheel leg curl [54]. An improved understanding of the acute and chronic effects of other common hamstring exercises on known or proposed risk factors for hamstring injury is needed to inform the design of intervention studies which may one day prove to be effective in reducing hamstring injury rates.

The acute patterns of hamstring muscle activation during different exercises are extremely heterogeneous. Studies employing sEMG are somewhat variable, however those employing fMRI have consistently demonstrated relatively more biceps femoris long head and semimembranosus activity during hip-extension oriented movements (i.e., stiff leg deadlifts), and relatively more semitendinosus and biceps femoris short head activation during knee-flexion oriented movements (i.e., Nordic hamstring exercise and leg curls) (Figure 1). On the basis of these findings, it seems logical to prescribe athletes a combination of both hip and knee dominant movements to effectively target all heads of the hamstrings. However, it remains unclear as to how important the magnitude or patterns of hamstring activation are in stimulating positive adaptations in these muscles. Recent evidence suggests that transient T2 shifts observed after a single bout of exercise may be associated with hypertrophy following a period of training (Figure 5) [29], which suggests the possibility that fMRI may be used to select exercises that target specific muscles or portions of muscles in injury prevention or rehabilitation programmes. However, further work is required to clarify this hypothesis and to determine the impact of muscle activation on the architectural and functional adaptations to a period of training.

It should be acknowledged that while the research findings discussed in this review may inform the design of strength training interventions for the prevention of first-time hamstring injury, it remains unknown as to whether they may also be applicable to injury rehabilitation practices. Given evidence of altered hamstring activation [23], architecture [84] and morphology [101], long after a return to sport from hamstring strain, it is possible that previously injured individuals will respond differently to strength training stimuli. Therefore, exploration of the acute responses and chronic adaptations of previously injured hamstrings to common rehabilitation exercises should be a focus of future research.

8. Conclusion

While strength training appears to be an effective means of reducing hamstring injury rates, the acute responses and chronic adaptations to training with different exercises are non-uniform. An improved understanding of this empirical evidence may enable practitioners to make better informed decisions around exercise selection for the prevention or treatment of hamstring strain injury. These data may also inform the design of training interventions, which may one day prove effective in reducing hamstring injury rates in sport.

Compliance with Ethical Standards

Funding

No sources of funding were used to assist in the preparation of this article.

Conflicts of Interest

Anthony Shield and David Opar are listed as co-inventors on a patent filed for a field test of eccentric hamstring strength (PCT/AU2012/001041.2012) as well as being shareholders in a company responsible for commercialising the device. Matthew Bourne, Ryan Timmins, Tania Pizzari, Joshua Ruddy, Casey Sims and Morgan Williams declare that they have no conflicts of interest relevant to the content of this review.

References

1. Opar DA, Williams MD, Shield AJ. Hamstring strain injuries: factors that lead to injury and re-injury. Sports Med. 2012;42(3):209-26.

2. Ekstrand J, Walden M, Hagglund M. Hamstring injuries have increased by 4% annually in men's professional football, since 2001: a 13-year longitudinal analysis of the UEFA Elite Club injury study. Br J Sports Med. 2016;50(12):731-7.

3. Ekstrand J, Lee JC, Healy JC. MRI findings and return to play in football: a prospective analysis of 255 hamstring injuries in the UEFA Elite Club Injury Study. Br J Sports Med. 2016;50(12):738-43.

4. Hagglund M, Walden M, Magnusson H, et al. Injuries affect team performance negatively in professional football: an 11-year follow-up of the UEFA Champions League injury study. Br J Sports Med. 2013;47(12):738-42.

5. Ekstrand J. Keeping your top players on the pitch: the key to football medicine at a professional level. Br J Sports Med. 2013;47(12).

6. Connell DA, Schneider-Kolsky ME, Hoving JL, et al. Longitudinal study comparing sonographic and MRI assessments of acute and healing hamstring injuries. Am J Roentgenol. 2004;183(4):975-84.

7. Koulouris G, Connell DA, Brukner P, et al. Magnetic resonance imaging parameters for assessing risk of recurrent hamstring injuries in elite athletes. Am J Sports Med. 2007;35(9):1500-6.

8. Verrall GM, Slavotinek JP, Barnes PG, et al. Diagnostic and prognostic value of clinical findings in 83 athletes with posterior thigh injury: comparison of clinical findings with magnetic resonance imaging documentation of hamstring muscle strain. Am J Sports Med. 2003;31(6):969-73.

9. McCall A, Dupont G, Ekstrand J. Injury prevention strategies, coach compliance and player adherence of 33 of the UEFA Elite Club Injury Study teams: a survey of teams' head medical officers. Br J Sports Med. 2016;50(12):725-30.

10. Donaldson A, Cook J, Gabbe B, et al. Bridging the gap between content and context: establishing expert consensus on the content of an exercise training program to prevent lower-limb injuries. Clin J Sport Med. 2015;25(3):221-9.

11. Brukner P, Nealon A, Morgan C, et al. Recurrent hamstring muscle injury: applying the limited evidence in the professional football setting with a seven-point programme. Br J Sports Med. 2014;48(11):929-38.

12. Arnason A, Andersen TE, Holme I, et al. Prevention of hamstring strains in elite soccer: an intervention study. Scand J Med Sci Sports. 2008;18(1):40-8.

13. Askling CM, Tengvar M, Tarassova O, et al. Acute hamstring injuries in Swedish elite sprinters and jumpers: a prospective randomised controlled clinical trial comparing two rehabilitation protocols. Br J Sports Med. 2014;48(7):532-9.

14. Askling CM, Tengvar M, Thorstensson A. Acute hamstring injuries in Swedish elite football: a prospective randomised controlled clinical trial comparing two rehabilitation protocols. Br J Sports Med. 2013;47(15):953-9.

15. Petersen J, Thorborg K, Nielsen MB, et al. 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.

16. Seagrave RA, 3rd, Perez L, McQueeney S, et al. Preventive effects of eccentric training on acute hamstring muscle injury in professional baseball. Orthop J Sports Med. 2014;2(6):2325967114535351.

17. van der Horst N, Smits DW, Petersen J, et al. The preventive effect of the Nordic hamstring exercise on hamstring injuries in amateur soccer players: a randomized controlled trial. Am J Sports Med. 2015;43(6):1316-23.

18. Bahr R, Thorborg K, Ekstrand J. Evidence-based hamstring injury prevention is not adopted by the majority of Champions League or Norwegian Premier League football teams: the Nordic Hamstring survey. Br J Sports Med. 2015;49(22):1466-71.

19. Orchard J, Seward H. Epidemiology of injuries in the Australian Football League; seasons 1997-2000. Br J Sports Med. 2002;36(1):39-44.

20. Seward H, Orchard J, Hazard H, et al. Football injuries in Australia at the elite level. Med J Aust. 1993;159:298-301.

21. Opar DA, Drezner J, Shield A, et al. Acute hamstring strain injury in track-and-field athletes: A 3-year observational study at the Penn Relay Carnival. Scand J Med Sci Sports. 2013; 24(4):e254-9.

22. Brooks JHM, Fuller CW, Kemp SPT, et al. Epidemiology of injuries in English professional rugby union: part 1 match injuries. Br J Sports Med. 2005;39:757-66.

23. Bourne MN, Opar DA, Al Najjar A, et al. Impact of exercise selection on hamstring muscle activation. Br J Sports Med. 2017;51(13):1021-1028.

24. Bourne M, Opar DA, Williams, MD, et al. Muscle activation patterns in the Nordic hamstring exercise: Impact of prior strain injury. Scand J Med Sci Sports. 2015;26(6):666-74.

25. Mendiguchia J, Garrues MA, Cronin JB, et al. Nonuniform changes in MRI measurements of the thigh muscles after two hamstring strengthening exercises. J Strength Cond Res. 2013;27(3):574-81.

26. Mendiguchia J, Arcos AL, Garrues MA, et al. The use of MRI to evaluate posterior thigh muscle activity and damage during Nordic Hamstring exercise. J Strength Cond Res. 2013;27(12):3426-35.

27. Ono T, Okuwaki T, Fukubayashi T. Differences in activation patterns of knee flexor muscles during concentric and eccentric exercises. Res Sports Med. 2010;18(3):188-98.

28. Ono T, Higashihara A, Fukubayashi T. Hamstring functions during hip-extension exercise assessed with electromyography and magnetic resonance imaging. Res Sports Med. 2011;19(1):42-52.

29. Bourne MN, Timmins RG, Williams MD, et al. Impact of the Nordic hamstring and hip extension exercises on hamstring architecture and morphology: implications for injury prevention. Br J Sports Med. 2017;51(5):469-477.

30. Timmins RG, Ruddy JD, Presland J, et al. Architectural changes of the biceps femoris after concentric or eccentric training. Med Sci Sports Exerc. 2015;48(3):499-508.

31. 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): p. 939-944.

32. Guex K, Millet GP. Conceptual framework for strengthening exercises to prevent hamstring strains. Sports Med. 2013;43(12):1207-15.

33. Malliaropoulos N, Mendiguchia J, Pehlivanidis H, 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.

34. Sherry MA, Johnston TS, Heiderscheit BC. Rehabilitation of acute hamstring strain injuries. Clin Sports Med. 2015;34(2):263-84.

35. Heiderscheit BC, Sherry MA, Silder A, et al. Hamstring strain injuries: Recommendations for diagnosis, rehabilitation and injury prevention. J Orthop Sports Phys Ther. 2010;40(2):67.

36. Burkett LN. Causative factors in hamstring strains. Med Sci Sports Exerc. 1970;2(1):39-42.

37. Garrett W, Safran M, Seaber AV, et al. Biomechanical comparison of stimulated and nonstimulated skeletal muscle pulled to failure. Am J Sports Med. 1987;15(6):448-54.

38. 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):309-14.

39. Croisier JL, Forthomme B, Namurois MH, et al. Hamstring muscle strain recurrence and strength performance disorders. Am J Sports Med. 2002;30(2):199-203.

40. Fousekis K, Tsepis E, Poulmedis P, et al. Intrinsic risk factors of non-contact quadriceps and hamstring strains in soccer: a prospective study of 100 professional players. Br J Sports Med. 2011;45(9):709-14.

41. Sugiura Y, Saito T, Sakuraba K, et al. 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):457-64.

42. van Dyk N, Bahr R, Whiteley R, et al. Hamstring and quadriceps isokinetic strength deficits are weak risk factors for hamstring strain injuries: a 4-year cohort study. Am J Sports Med. 2016;44(7):1789-95.

43. Opar DA, Williams MD, Timmins RG, et al. Eccentric hamstring strength and hamstring injury risk in Australian footballers. Med Sci Sports Exerc. 2014;47(4):857-65.

44. Timmins R, Bourne M, Shield A, et al. Short biceps femoris fascicles and eccentric knee flexor weakness increase the risk of hamstring injury in elite football (soccer): a prospective cohort study. Br J Sports Med. 2015;50(24):1524-1535.

45. Bourne M, Opar DA, Williams M, et al. Eccentric knee-flexor strength and hamstring injury risk in rugby union: a prospective study. Am J Sports Med. 2015;43(11):2663-70.

46. Croisier JL, Ganteaume S, Binet J, et al. Strength imbalances and prevention of hamstring injury in professional soccer players: a prospective study. Am J Sports Med. 2008;36(8):1469-75.

47. 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.

48. Opar DA, Piatkowski T, Williams MD, et al. A novel device using the Nordic hamstring exercise to assess eccentric knee flexor strength: a reliability and retrospective injury study. J Orthop Sports Phys Ther. 2013;43(9):636-40.

49. Dauty M, Menu P, Fouasson-Chailloux A, et al. Prediction of hamstring injury in professional soccer players by isokinetic measurements. Muscles Ligaments Tendons J. 2016;6(1):116-23.

50. Cameron M, Adams R, Maher C. Motor control and strength as predictors of hamstring injury in elite players of Australian football. Phys Ther Spor. 2003;4(4):159-66.

51. Orchard J, Marsden J, Lord S, et al. Preseason hamstring muscle weakness associated with hamstring muscle injury in Australian footballers. Am J Sports Med. 1997;25(1):81-5.

52. Zvijac JE, Toriscelli TA, Merrick S, et al. Isokinetic concentric quadriceps and hamstring strength variables from the NFL Scouting Combine are not predictive of

hamstring injury in first-year professional football players. Am J Sports Med. 2013;41(7):1511-8.

53. Goossens L, Witvrouw E, Vanden Bossche L, et al. Lower eccentric hamstring strength and single leg hop for distance predict hamstring injury in PETE students. Eur J Sport Sci. 2015;15(5):436-42.

54. 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.

55. Mjolsnes R, Arnason A, Osthagen T, et al. 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.

56. Engebretsen AH, Myklebust G, Holme I, et al. Prevention of injuries among male soccer players: a prospective, randomized intervention study targeting players with previous injuries or reduced function. Am J Sports Med. 2008;36(6):1052-60.

57. Tyler TF, Schmitt BM, Nicholas SJ, et al. Rehabilitation after hamstring strain injury emphasizing eccentric strengthening at long muscle lengths: results of long term follow-up. J Sport Rehabil. 2016;24:1-33.

58. Wakahara T, Miyamoto N, Sugisaki N, et al. Association between regional differences in muscle activation in one session of resistance exercise and in muscle hypertrophy after resistance training. Eur J Appl Physiol. 2012;112(4):1569-76.

59. Wakahara T, Fukutani A, Kawakami Y, et al. Nonuniform muscle hypertrophy: its relation to muscle activation in training session. Med Sci Sports Exerc. 2013;45(11):2158-65.

60. Zebis MK, Skotte J, Andersen CH, et al. Kettlebell swing targets semitendinosus and supine leg curl targets biceps femoris: an EMG study with rehabilitation implications. Br J Sports Med. 2013;47(18):1192-8.

61. Ditroilo M, De Vito G, Delahunt E. Kinematic and electromyographic analysis of the Nordic Hamstring Exercise. J Electromyogr Kinesiol. 2013;23(5):1111-8.

62. Farina D, Merletti R, Enoka RM. The extraction of neural strategies from the surface EMG. J Appl Physiol. 2004;96(4):1486-95.

63. Veiersted KB. The reproducibility of test contractions for calibration of electromyographic measurements. Eur J Appl Physiol Occup Physiol. 1991;62(2):91-8.

64. Adams GR, Duvoisin MR, Dudley GA. Magnetic resonance imaging and electromyography as indexes of muscle function. J Appl Physiol (1985). 1992;73(4):1578-83.

65. Arendt-Nielsen L, Zwarts M. Measurement of muscle fiber conduction velocity in humans: techniques and applications. J Clin Neurophysiol. 1989;6(2):173-90.

66. Yao W, Fuglevand RJ, Enoka RM. Motor-unit synchronization increases EMG amplitude and decreases force steadiness of simulated contractions. J Neurophysiol. 2000;83(1):441-52.

67. Tsaklis P, Malliaropoulos N, Mendiguchia J, et al. Muscle and intensity based hamstring exercise classification in elite female track and field athletes: implications for exercise selection during rehabilitation. Open Access J Sports Med. 2015;6:209-17.

68. Fleckenstein JL, Canby RC, Parkey RW, et al. Acute effects of exercise on MR imaging of skeletal muscle in normal volunteers. AJR Am J Roentgenol. 1988;151(2):231-7.

69. Fisher MJ, Meyer RA, Adams GR, et al. Direct relationship between proton T2 and exercise intensity in skeletal muscle MR images. Invest Radiol. 1990;25(5):480-5.

70. Cagnie B, Elliott JM, O'Leary S, et al. Muscle functional MRI as an imaging tool to evaluate muscle activity. J Orthop Sports Phys Ther. 2011;41(11):896-903.

71. Fleckenstein JL, Haller RG, Lewis SF, et al. Absence of exercise-induced MRI enhancement of skeletal muscle in McArdle's disease. J Appl Physiol (1985). 1991;71(3):961-9.

72. Shellock FG, Fukunaga T, Mink JH, et al. Acute effects of exercise on MR imaging of skeletal muscle: concentric vs eccentric actions. AJR Am J Roentgenol. 1991;156(4):765-8.

73. Fernandez-Gonzalo R, Tesch PA, Linnehan RM, et al. Individual muscle use in hamstring exercises by soccer players assessed using functional MRI. Int J Sports Med. 2016;37(7):559-64.

74. Jenner G, Foley JM, Cooper TG, et al. Changes in magnetic resonance images of muscle depend on exercise intensity and duration, not work. J Appl Physiol (1985). 1994;76(5):2119-24.

75. Patten C, Meyer RA, Fleckenstein JL. T2 mapping of muscle. Semin Musculoskelet Radiol. 2003;7(4):297-305.

76. Delahunt E, McGroarty M, De Vito G, et al. Nordic hamstring exercise training alters knee joint kinematics and hamstring activation patterns in young men. Eur J Appl Physiol. 2016;116(4):663-72.

77. Jakobsen MD, Sundstrup E, Andersen CH, et al. Effectiveness of hamstring knee rehabilitation exercise performed in training machine vs. elastic resistance: electromyography evaluation study. Am J Phys Med Rehabil. 2014;93(4):320-7.

78. McAllister MJ, Hammond KG, Schilling BK, et al. Muscle activation during various hamstring exercises. J Strength Cond Res. 2014;28(6):1573-80.

79. Messer DM, Bourne MN, Williams MD, et al. Knee flexor muscle use in females during hip-extension and the Nordic hamstring exercise: an fMRI study. J Orthop Sports Phys Ther. In Review.

80. Bourne MN, Williams MD, Pizzari T, et al. A functional MRI exploration of hamstring activation during the supine bridge exercise. Int J Sports Med. In Review.

81. Evans G, Haller RG, Wyrick PS, et al. Submaximal delayed-onset muscle soreness: correlations between MR imaging findings and clinical measures. Radiology. 1998;208(3):815-20.

82. Fleckenstein J, Weatherall P, Parkey R, et al. Sports-related muscle injuries: evaluation with MR imaging. Radiology. 1989;172(3):793-8.

83. Kubota J, Ono T, Megumi A, et al. Non-uniform changes in magnetic resonance measurements of the semitendinosus muscle following intensive eccentric exercise. Eur J Appl Physiol. 2007;101:713-20.

84. Timmins RG, Shield AJ, Williams MD, et al. Biceps femoris long head muscle architecture a reliability and retrospective injury study. Med Sci Sports Exerc. 2015;43(11):2663-70.

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

86. Timmins RG, Shield AJ, Williams MD, et al. Architectural adaptations of muscle to training and injury: a narrative review outlining the contributions by fascicle length, pennation angle and muscle thickness. Br J Sports Med. 2017;51(6):547-548.

87. Duhig S. Hamstring Strain Injury: Effects of high-speed running, kicking and concentric versus eccentric strength training on injury risk and running recovery. 2017. Doctoral Thesis. Queensland University of Technology, QUT ePrints. 2017.

88. Presland J, Timmins RG, Williams MD, et al. The effect of high or low volume Nordic hamstring training on biceps femoris long head architectural adaptations. Scand J Med Sci Sports. In Review.

89. Breno de A R Alvares J, Marques VB, Vaz MA, et al. Four weeks of Nordic hamstring exercise reduce muscle injury risk factors in young adults. J Strength Cond Res. 2017;doi: 10.1519/JSC.0000000000001975. [Epub ahead of print].

90. Alonso-Fernandez D, Docampo-Blanco P, Martinez-Fernandez J. Changes in muscle architecture of biceps femoris induced by eccentric strength training with Nordic hamstring exercise. Scand J Med Sci Sports. 2017;doi: 10.1111/sms.12877. [Epub ahead of print]

91. Lovell R, Knox M, Weston M, et al. Hamstring injury prevention in soccer: Before or after training? Scand J Med Sci Sports. 2017; doi:10.1111/sms.12925. [Epub ahead of print].

92. Guex K, Degache F, Morisod C, et al. Hamstring architectural and functional adaptations following long vs. short muscle length eccentric training. Front Physiol. 2016;7:340.

93. Seymore KD, Domire ZJ, DeVita P, et al. The effect of Nordic hamstring strength training on muscle architecture, stiffness, and strength. Eur J Appl Physiol. 2017;117(5):943-53.

94. Evangelidis PE, Massey GJ, Pain MT, et al. Biceps femoris aponeurosis size: a potential risk factor for strain injury? Med Sci Sports Exerc. 2015;47(7):1383-9.

95. Fiorentino NM, Epstein FH, Blemker SS. Activation and aponeurosis morphology affect in vivo muscle tissue strains near the myotendinous junction. J Biomech. 2012;23;45(4):647-52.

96. Rehorn MR, Blemker SS. The effects of aponeurosis geometry on strain injury susceptibility explored with a 3D muscle model. J Biomech. 2010;43(13):2574-81.

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

98. Wakahara T, Ema R, Miyamoto N, et al. Increase in vastus lateralis aponeurosis width induced by resistance training: implications for a hypertrophic model of pennate muscle. Eur J Appl Physiol. 2015;115(2):309-16.

99. Abe T, Kumagai K, Bemben MG. Muscle aponeurosis area is greater in hypertrophied than in normal muscle. J Gen Intern Med. 2012;27:399.

100. Jakobsen JR, Mackey AL, Knudsen AB, et al. Composition and adaptation of human myotendinous junction and neighboring muscle fibers to heavy resistance training. Scand J Med Sci Sports. 2016; doi: 10.1111/sms.12794. [Epub ahead of print]

101. Silder A, Heiderscheit BC, Thelen DG, et al. MR observations of long-term musculotendon remodeling following a hamstring strain injury. Skeletal Radiol. 2008;37(12):1101-9.

102. Blazevich AJ, Coleman DR, Horne S, et al. Anatomical predictors of maximum isometric and concentric knee extensor moment. Eur J Appl Physiol. 2009;105(6):869-78.

103. Seymore KD. The effect of eccentric hamstring strength training on muscle function. Masters Thesis. East Carolina University, ProQuest Dissertations Publishing. 2015;1590159.

104. Iga J, Fruer CS, Deighan M, et al. 'Nordic' hamstrings exercise - engagement characteristics and training responses. Int J Sports Med. 2012;33(12):1000-4.

105. Goode AP, Reiman MP, Harris L, et al. Eccentric training for prevention of hamstring injuries may depend on intervention compliance: a systematic review and meta-analysis. Br J Sports Med. 2015;49(6):349-56.

106. Guex KJ, Lugrin V, Borloz S, et al. Influence on strength and flexibility of a swing phase-specific hamstring eccentric program in sprinters' general preparation. J Strength Cond Res. 2016;30(2):525-32.

107. Holcomb WR, Rubley MD, Lee HJ, et al. Effect of hamstring-emphasized resistance training on hamstring:quadriceps strength ratios. J Strength Cond Res. 2007;21(1):41-7.

108. Mendiguchia J, Martinez-Ruiz E, Morin JB, et al. Effects of hamstring-emphasized neuromuscular training on strength and sprinting mechanics in football players. Scand J Med Sci Sports. 2015;25(6):e621-9.

109. Brockett C, Morgan D, Proske U. Human hamstring muscles adapt to eccentric exercise by changing optimum length. Med Sci Sports Exerc. 2001;33(5):783-90.

110. Clark R, Bryant A, Culgan J-P, et al. 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.

111. Brughelli M, Mendiguchia J, Nosaka K, et al. 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.

112. 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.