# Optimising Hamstring Strength and Function for Performance After Hamstring Injury

## 12

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## 12.1 Introduction

One major premise of the current chapter is that high levels of sport-specific fitness and strength will likely be associated with a reduced risk of non-contact injury. This argument is supported by observational studies which link higher volumes of training with a lower incidence of sports injuries (e.g. [1–3]). Furthermore, there is some evidence that stronger, faster [4] and fitter [5] athletes are more resistant to the injuries associated with high workloads and load 'spikes'; the latter of which are often experienced with hurried returns to competition. Obviously, effective strategies for enhancing athlete fitness do not focus specifically on the hamstrings. However, another premise of this chapter is that there are some persistent deficits in neuromuscular function after moderate to severe hamstring strain injuries (HSIs) [6], and these deserve some attention during rehabilitation and even after the return to sport (RTS). It has been proposed that neuromuscular inhibition of previously injured hamstring muscles may account for the persistence of deficits in sprint performance, eccentric weakness, muscle atrophy and short fascicles despite adherence to conventional rehabilitation programmes.

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## 12.2 Deficits in Neuromuscular Function After Hamstring Strain Injury

A number of the neuromuscular deficits associated with prior hamstring injury persist through conventional rehabilitation and remain evident well after the return to full training and competition schedules [6]. For example, deficits in the horizontal ground reaction forces of sprinting have been revealed in athletes well after their return to play [7, 8], sometimes as much as 1 year post-injury [8]. Furthermore, a history of hamstring injury is also associated with a greater loss of horizontal ground reaction forces during repeated 6-s sprints [8]. There are also reports of eccentric weakness [9–11] and reductions in rate of torque development [12] in athletes ~1–36 months after injury despite a full RTS. Lee and colleagues [10], for example, reported ~10% and ~13% deficits in peak eccentric knee flexor work and torque, respectively, in athletes who had incurred grade 2 or 3 injuries 19 ± 12.5 months prior to isokinetic testing. There has also been a report of deficits in biceps femoris long head ($BF_{LH}$) muscle volume 5–23 months post-injury [13]. Finally, previously injured biceps femoris (BF) muscles also have shorter fascicles than uninjured muscles after the RTS [14, 15], and these deficits persist from one season to the next and are not normalised by preseason training in elite Australian footballers [14]. It is important to acknowledge that these deficits are revealed by comparisons between previously injured and uninjured limbs, and the retrospectivity of these observations prevents the firm conclusion that these are the result of injury. As a result, it might be argued that these between-limb differences predated original injuries.

The persistence of inelastic scar tissue, described more fully in Chap. 2, is another long-term detrimental consequence of muscle strain injury. This fibrous tissue may persist for months to years [13, 16] and increase strain in the adjacent portions of the muscle [17], thereby increasing the risk of injury recurrence. It is also plausible that unrecognised risk factors or a complex interaction of risk factors may persist through rehabilitation and thereby contribute to injury recurrence [18].

### 12.2.1 Do Neuromuscular Deficits Contribute to Injury Recurrence?

While many of the commonly cited neuromuscular risk factors for HSI and recurrence are not well-supported [19, 20] (see also Chap. 4), it is possible that deficits in strength or fascicle length may still contribute to a heightened risk of injury recurrence via interactions with other factors such as age and previous injury [21, 22] as discussed in Chap. 5.

### 12.2.2 Why Do These Deficits Persist?

Regardless of whether or not neuromuscular deficits are caused by HSI, their persistence might be interpreted as evidence of absent or inadequate rehabilitation.

Parameters such as ground reaction forces in acceleration, strength and muscle fascicle length are all trainable. However, despite rehabilitation (the details of which are often not reported in retrospective studies), many of these deficits persist in elite and sub-elite athletes who have returned to full training and competition, sometimes for more than a year. Presumably, this level of competition requires adherence to reasonably effective training programmes, and there has been no convincing explanation as to why fascicles stay short, muscles remain atrophied and ground reaction forces diminished many months and sometimes years after HSI.

We have proposed that neuromuscular inhibition, initially induced by muscle pain and isolated to previously injured muscles, may sabotage hamstring rehabilitation and contribute to the relative permanence of maladaptations after moderate to severe strain injuries [23, 24]. Fig. 12.1 shows a theoretical model (adapted from Fyfe et al. [23]) that has been modified to include the possible effects of fatigue created by repeated sprint running. This inhibition reduces muscle activation during eccentric contractions, which would otherwise provide a powerful stimulus for positive adaptations such as strength gain and fascicle lengthening. For example, Bourne and colleagues [25] employed functional magnetic resonance imaging (fMRI) to show that the previously injured $BF_{LH}$ was ~30% less active than the uninjured homologous muscle during the Nordic hamstring exercise (NHE), after the full RTS and 2–24 months after injury (mean = 9.8 ± 8.7 months). There is also evidence that the BF surface electromyogram (sEMG) in maximal eccentric actions is lower, when normalised to the maximal concentric sEMG, in limbs with a history of hamstring strains than in uninjured contralateral muscles 2–18 months after injury (mean = 5.3 months) [11]. Furthermore, a pilot study employing twitch interpolation suggests that hamstring voluntary activation after injury is reduced during maximal eccentric, but not maximal concentric knee flexor contractions [26]. This reduction in activation may also be evident during running [27] and might explain the persistence of short $BF_{LH}$ fascicles in previously injured athletes [14, 15] despite the use of otherwise effective training methods. The relative permanence of these maladaptations is consistent with the chronic nature of central nervous system responses to muscle pain that have previously been reported (e.g. [28, 29]).

While some aspects of the neuromuscular inhibition model have been supported, there is currently no direct evidence that it explains high hamstring injury recurrence rates. Further work is required to show that reversing neuromuscular inhibition also results in restoration of normal fascicle lengths and a marked reduction in injury recurrence rates.

Not all studies have reported neuromuscular inhibition after HSI. Blandford and colleagues [30] assessed hamstring sEMG during the eccentric NHE and normalised it to that obtained from maximal isometric contractions in elite youth soccer players with and without a history of HSI. This study showed higher normalised BF sEMG during the NHE in injured than uninjured limbs, although a number of methodological issues prevent valid comparisons with previous findings. Firstly, normalising eccentric to isometric sEMG may well give different results to those observed when

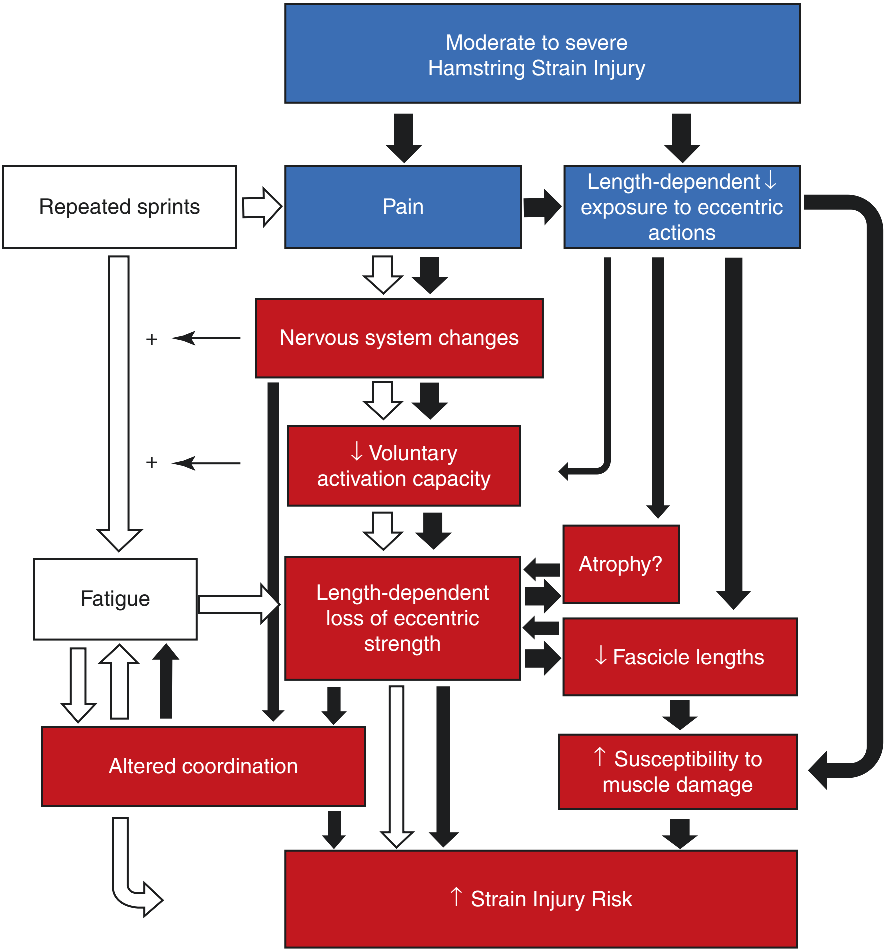

**Fig. 12.1** A theoretical model that attempts to explain the role of neuromuscular inhibition in creating deficits in eccentric strength and muscle damage resistance, thereby increasing the risk of injury recurrence. The possible effects of fatigue during repeated sprinting and coordination changes have been added since original publication [23]. Unfilled boxes and arrows show the acute effects of repeat sprinting. The amplification of sprint-induced fatigue in previously injured athletes is shown with '+' symbols. Blue boxes show the transient effects of injury (lasting weeks to months). Red boxes show the chronic effects which, when caused by moderate to severe strain injury, often persist through rehabilitation and may still be present months to years after the return to sport. Altered coordination may occur at intramuscular (between hamstrings) and intermuscular (between hamstrings and their synergists) levels as discussed in Chap. 5

normalising eccentric to concentric sEMG [11]. If both eccentric and isometric contractions are inhibited, the former method would not differentiate between injured and uninjured muscles, and normalisation to concentric sEMG is based on the relative preservation of concentric strength that has been observed in a number of studies [9–11, 18]. A recent observation of persistent isometric weakness one to three seasons after HSI [31] suggests the possibility that this contraction mode is not the most appropriate one to which others are normalised. Secondly, Blandford and colleagues [30] did not report the muscles affected or the severity of the injuries in their cohort. However, inhibition has been reported to be muscle specific [25], and it has been proposed that only moderate to severe hamstring injuries will result in lasting deficits in voluntary activation capacity [23]. In fact, recent work from one of the authors' laboratories showed no between-limb differences in eccentric or isometric strength in participants with a unilateral history of grade 1 hamstring injuries, although previously injured BF muscles did have shorter long head fascicles than the uninjured BF muscles [32].

An addition to the original neuromuscular inhibition model for hamstring injury recurrence [23] is the hypothesised interaction between the fatiguing effects of repeated sprinting and hamstring muscle activation (Fig. 12.1). As discussed in more detail later in this chapter, certain performance-related aspects of repeated sprinting decline with fatigue, and this decline seems to be greater in previously injured athletes than in those without a history of hamstring strain [33]. The new elements of the model hypothesise that repeated sprinting results in acute reductions in hamstring voluntary activation (central fatigue/neuromuscular inhibition), regardless of hamstring injury history. Reductions in maximal voluntary quadriceps activation have been reported for the quadriceps muscles after repeated 30 m sprints [34], although, as far as we are aware, no similar studies of hamstring muscle activation exist. However, Timmins and colleagues [35] have reported that repeated sprinting resulted in reductions in eccentric knee flexor strength that were associated with a decline in the BF, but not medial hamstring sEMG. Furthermore, the fatiguing effects of sprinting are not proposed to be limited to the hamstrings. A decline in the coordination of a number of lumbopelvic muscles could also potentially increase the risk of hamstring strains as discussed more fully in Chap. 5.

## 12.3 Addressing Deficits in Sprint Performance

### 12.3.1 Avoiding Spikes in Sprinting Workloads

Rapid increases in high-speed running loads are associated with an elevated risk of HSI in elite Australian rules footballers [36, 37]. These observations add to the broader literature which suggests that a gradual progression in training load assists in minimising injury risk. So, while the pressure for an early return to play after any form of injury may encourage some risk taking, consideration should be given to the benefits of a slightly delayed return as this enables the more gradual accumulation of sprint running volumes [3].

### 12.3.2 Ground Reaction Forces

It has been suggested that the hamstrings provide a particularly significant proportion of the horizontally oriented ground reaction force in sprinting [38], and a compelling argument has been made for monitoring these forces and emphasising this aspect of performance during hamstring rehabilitation and after the RTS [7, 39, 40]. Furthermore, relatively inexpensive technologies (iPhone, timing gates or Rader gun) have been found to be valid ways of estimating these forces and other aspects of the force-velocity profile of sprinting [41, 42].

The optimal methods for improving horizontal ground reaction forces after HSI are not yet known, although an argument can be made for resisted sprinting such as sled pulling. A systematic review by Alcaraz and colleagues [43] suggests that while both sled pulling and unresisted sprinting are effective at improving acceleration phase sprint performance, sled training is not superior to conventional (unloaded) running. However, a majority of sled training studies have employed light loads (<20% body mass) and assessed sprint performance rather than ground reaction forces [43]. Morin and colleagues [44] have recently made a case for the benefits of unconventionally heavy (80% of body mass) sled training in improving force application and acceleration capacity in uninjured soccer players. These authors observed slight benefits in favour of sled training over conventional unloaded sprint training in terms of maximal force application, maximal power and the direction of force application (it became more horizontal) after 8 weeks of training. Sled training sessions in this study involved five to eight 20 m sprints twice each week, in training segments that took approximately 21 min to complete, so this form of training appears to be particularly time efficient [44]. Further research on the optimal means of improving force application to the ground, particularly in previously injured athletes, is warranted.

### 12.3.3 Repeated Sprint Ability

As mentioned previously, Australian rules footballers with a history of hamstring injuries show greater losses in horizontal ground reaction forces, on the side of injury, during repeated treadmill sprints (ten repetitions of 6-s sprints interspersed with 24-s of jogging) [8]. Previously injured limbs exhibited ~13% reductions in horizontal ground reaction forces, while the contralateral limbs and both limbs of control players exhibited ~3% drop-offs [8]. Roksund and colleagues [45] showed that the decline in repeated 20 m sprint performance across eight repetitions (with 30 s recovery) was greater in soccer players with a history of hamstring injury in the previous 2 years than in players without injury in that time. However, athletes with a history of hamstring injury in this study were faster during the initial 20 m sprints than control participants and despite exhibiting greater rates of fatigue they ran their final sprints in a virtually identical time to that of the control players [45].

Until relatively recently, there had been little research regarding the optimal training methods to improve repeated sprint ability [46]. The fatigue experienced during repeated sprints is likely mediated by depletion of energy substrates, deficits in aerobic and anaerobic metabolism and the build-up of waste-products such as inorganic phosphate and the hydrogen ion [47, 48]. However, recent observations suggest that an inability to fully activate the working muscles, presumably as a consequence of central fatigue, may be another important factor limiting performance during this type of activity [34, 49]. Because repeated sprint ability depends on both sprint performance and the ability to recover between sprints, it is sensible to prioritise the development of both of these factors [46]. Maximal running velocity can be developed via a combination of specific sprint training (short sprints separated by recovery periods of three or more minutes) [50] and strength and power training. Given the major role of the hamstrings in generating horizontal velocity [38], interventions aimed at improving strength, power and activation of these muscles and their synergists, particularly after injury, may be important in improving sprint performance. It has been argued that fatigue resistance during repeat sprint efforts is best improved via high-intensity (80–90% VO2 max) interval training [46]. This type of training, with work to rest ratios >1, has been shown to simultaneously improve aerobic fitness [51], phosphocreatine resynthesis [52] and $H^+$ buffering capacity [53], all of which potentially limit performance during repeated sprints.

Running protocols designed to simulate the demands of soccer matches result in significant acute reductions in knee flexor strength, particularly in eccentric actions [54–56]. It has been proposed that these declines may contribute to the increasing likelihood of HSIs across each 40–45 min 'half' in rugby [57] and soccer [58]. There are a small number of training studies that have been shown to reduce this running-induced decline in eccentric strength. Small and colleagues [56] reported that eccentric knee flexor strength loss (after 90 min of the SAFT running protocol) was significantly reduced after an 8-week period of eccentric strength training with the NHE. However, this effect was noted when the NHE exercises were performed after, but not before, on-field soccer training sessions [56]. More recently, Matthews and colleagues [59] demonstrated that 4 weeks of eccentric NHE training with strength (5 sets of 4 repetitions) and strength-endurance approaches (5 sets of 12 rubber band-assisted repetitions) had similar protective effects against the strength loss induced by a 45 min intermittent running protocol. Delextrat and colleagues [60] further investigated the effects of the two different approaches on strength loss induced by a 90 min running protocol in female soccer players. Ten players were randomly allocated to a strength training programme (3–5 sets of 6 repetitions with 3 min between sets), and 11 were assigned to a strength-endurance programme (3 sets of 12–20 repetitions with 45–90 s between sets), with all performing the seated leg curl and stiff leg dead lift over 7 weeks. In this study, only the strength-endurance approach resulted in reduced strength loss after running [60].

While the repeated sprinting demands of field and court sports are most specifically improved by running programmes, heavy resistance training may also contribute positively to the maintenance of eccentric strength during repeated sprinting. It is not currently clear whether strength-oriented (high intensity, low repetition) or strength-endurance-oriented (moderate intensity, medium to high repetition) training is optimal for this purpose; however, both approaches may work when purely eccentric or eccentrically biased exercises are employed.

### 12.3.4 Sprint Running Technique

As discussed in Chap. 5, there is now a small amount of evidence that aberrant lumbopelvic kinematics, in the form of elevated anterior pelvic tilt and lateral trunk flexion, are associated with a heightened risk of HSI [61]. However, it is important to recognise that this evidence comes from a prospective trial with 29 soccer players and just 4 prospective injuries [61]. So, while these results are promising, more work is required to show that these findings are robust.

Schuermans and colleagues [61] also compared 30 soccer players with previous HSIs with 30 control participants and reported that there were no discernible differences in the sprint kinematics observed between 15 and 25 m of maximal sprinting. These findings are seemingly at odds with another study in which nine Gaelic footballers with a history of hamstring injury exhibited greater anterior pelvic tilt, hip flexion and medial knee rotation during treadmill running (at 20 km. $h^{-1}$) than eight control athletes [27]. Unfortunately, neither study reported the severity of the previous injuries or the muscles in which they occurred, and it is possible that some were quite minor given the 7-day [61] and 2-day [27] minimum times for RTS which were employed to classify injuries. Nevertheless, it remains possible that prior hamstring injury may not always lead to lasting changes in the kinematic variables that have thus far been examined. Furthermore, coaches and clinicians, who might most often use the ‘naked eye’ to assess running technique, may not be able to reliably ‘see’ small changes of the sort reported by Daly and colleagues [27].

If lumbopelvic kinematics do contribute to hamstring injuries, the next great challenge for clinicians, coaches and researchers lies in determining the best methods for improving them. Optimising running technique may also be particularly challenging for athletes outside of track and field who typically have limited time to devote to such endeavours. The prospective study by Schuermans and colleagues [61] suggests that for athletes with excessive anterior pelvic tilt, a more upright trunk and pelvis position may help reduce hamstring injuries. However, it is not known whether excessive anterior tilt is indicative of poor strength, inadequate mobility or poor coordination and for now, training programmes may need to address all of these factors. Finally, it should be acknowledged that the evidence base for the role of kinematics in hamstring injury is scant, and there is considerable room for further research [62].

### 12.3.5 Sport-Specific Running Requirements

Athletes in ball sports frequently run at near-maximal speeds while twisting their trunks and turning their heads to observe the path of a ball or an opponent or to pass and receive a ball. Furthermore, hamstring injuries are sometimes observed when footballers flex at the hip and trunk to catch an imperfectly delivered pass [63]. Clearly, an appropriate focus on sport-specific conditioning (small-sided games or well-designed drills) will expose athletes to some high-speed running while twisting and/or stooping, although the total volume of these movements may not represent an adequate training stimulus. Running with a significant forward stoop (while paddling a ball along the ground) was one ‘drill’ in an apparently successful non-randomised intervention study by Verrall and colleagues [63] designed specifically for Australian Rules players. The combination of an increase in the volume of high-speed running (and a reduction in slower longer distance runs), hamstring stretching in a fatigued state and the ball paddling drill (used twice per week for 5 min each time) was shown to reduce the hamstring injury rate in one club from 27 in the two seasons prior to the intervention to 8 in the two subsequent seasons [63]. The design of this study, with its multiple interventions, prevents conclusions as to the effectiveness of each element of the programme. As a consequence, more research is required to establish that stooped running, as employed while paddling a ball, can reduce hamstring injury rates.

## 12.4 Addressing Deficits in Strength and Muscle Architecture

While post-rehabilitation conditioning for athletes need not focus unduly on previously injured muscles or on the aforementioned deficits (e.g. [64]), it is possibly advantageous to include some exercises and drills that effectively target them [21, 22]. Deficits in strength and fascicle lengths have been discussed in this and previous chapters, and there is an understandable inclination to address these specifically after the RTS. It should be noted, however, that the highest level of evidence comes from randomised controlled trials (RCTs), not the studies that have, inconsistently, shown associations between strength and hamstring injury rates. Furthermore, an association between BF fascicle lengths and injury rates have, at the time of publication, only been observed in a single study [22], which needs replication. As a consequence, the remainder of this chapter deals more generally with exercise selection for the hamstrings and other lumbopelvic muscles, addressing inhibition and the argument for including exercises with an eccentric bias.

### 12.4.1 Exercise Selection

A growing body of research has highlighted the heterogeneity of hamstring activation patterns in different tasks [25, 65–70] and the nonuniformity of muscle adaptations to different exercises [67]. In theory, this evidence should provide a framework for selecting exercises to induce specific adaptations in target muscles (or portions of those muscles) to reduce the risk of injury and enhance performance. However, this work appears to have had little influence on clinical exercise guidelines for hamstring injury prevention [71, 72] or rehabilitation [73, 74]. Understanding muscle activation and adaptation patterns in response to common hamstring exercises allows for specific targeting of individual hamstring muscles and their synergists with resistance training exercises. However, it must be recognised that none of the findings regarding muscle activation patterns constitute evidence for the efficacy of any particular exercise as a means of preventing injury or improving performance. Randomised controlled trials are needed before we can confidently state that any particular exercise or combination of exercises is effective.

#### 12.4.1.1 Methodological Issues in Assessing Muscle Activation

Skeletal muscle activation is an important determinant of the structural adaptations caused by strength training [75–77]. Studies of hamstring muscle activation patterns have employed either sEMG or fMRI to map the acute electrical or metabolic activity of the hamstrings in different tasks. Surface EMG measures the electrical activity generated by active motor units via electrodes that are placed on the skin overlying the target muscles. This technique provides an indirect assessment of activation with high temporal resolution. However, a major limitation of sEMG is its susceptibility to crosstalk from neighbouring muscles [78], and this makes it impossible to completely discriminate between muscles that lie close to each other such as the long and short heads of the BF or the semimembranosus (SM) and semitendinosus (ST) [66]. Surface EMG amplitude is also influenced by the amount of subcutaneous tissue [78], motor unit conduction velocities [79] and the degree to which motor unit firing is synchronous [80]. Another rarely appreciated limitation of sEMG studies is the normalisation process. Because sEMG signals in millivolts have no real significance, these amplitudes are normalised to the sEMG signal obtained during maximal voluntary contractions (MVCs). However, the MVCs are very often performed isometrically [66], and this typically dictates an arbitrary choice of joint angles (and muscle lengths) which may not be replicated during the exercises that are examined. For example, hamstring sEMG in a range of exercises might be normalised to that observed during an isometric leg curl at a fixed knee angle [66]. This is almost certainly not a valid means of normalising the sEMG observed during a hip extension exercise or even during a dynamic leg curl across a range of motion (ROM) because the volume of muscle immediately under the electrodes will change with muscle length. The choice of different normalisation ‘tasks’ very likely leads to different interpretations of sEMG results, and these limitations may explain the commonly observed discrepancies between sEMG studies. The limitations of normalisation are perhaps no better demonstrated than by observations that sEMG amplitudes in dynamic or isometric exercises are frequently higher than those observed in the task to which they are normalised [66]. This suggests that some muscles are not optimally activated during the chosen MVCs. For the abovementioned reasons, we recommend that exercise prescription guidelines should not be made on the basis of sEMG studies alone.

Functional MRI is based on the observation 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 [81, 82], can be mapped in cross-sectional images of muscle with excellent spatial resolution [83, 84]. However, fMRI involves scanning before and after exercise, so it does not provide insight into the timing or sequencing of muscle activation. T2 relaxation time changes are the consequence of osmotically driven fluid shifts between different muscle compartments caused by the buildup of metabolites of glycolysis. T2 changes will therefore be higher after concentric than eccentric exercise, because the former has a greater metabolic cost, even if muscle force and work duration are identical. The T2 response also varies with the duration of muscle activity and is dependent on the total work performed. As a consequence, it is problematic to compare T2 changes between exercises with different contraction modes or work durations. T2 responses to exercise are also influenced by muscle fibre type and the vascular dynamics of the active tissue [84, 85], and previous HSI is associated with diminished exercise-induced T2 changes during eccentric exercise [25]. Perhaps for these reasons, large differences in T2 changes can be observed between individuals despite them performing the same exercise with the same number of repetitions and relative intensities. It is therefore inadvisable to compare T2 changes between exercises that are performed by different participants (e.g. [86]). Despite these limitations, both sEMG and fMRI can yield valuable information on the extent and timing of muscle activation during exercise. Ideally, these observations should be verified by measurement of chronic adaptations caused by training, and this process has started in the case of hamstring exercises [67].

#### 12.4.1.2 Nordic Hamstring Exercise

A number of studies [66, 87, 88] have established that the NHE evokes very high levels of normalised EMG (nEMG) from both the BF (72–91% of that recorded in MVC) and medial hamstring (82–102% MVC). Early work suggested that the exercise may have preferentially recruited the BF over the medial hamstrings [88]; however, more recent studies have reported higher levels of medial hamstring than BF nEMG [66, 87]. Despite preferential medial hamstring activation, it should be noted that the nEMG of BF is considerably higher in the NHE than almost any other hamstring exercise studied to date [66, 87]; however, the intensity of this eccentric exercise (>the 1Repetition Maximum (RM) for most people) is also markedly higher than the concentric-eccentric exercises (typically with 6–12RM loads) to which it is compared. Nevertheless, the level of nEMG in the Nordic exercise is particularly remarkable when compared to the 10–60% values reported for the eccentric phases of eight common hamstring exercises [66].

Functional MRI studies [25, 66, 68, 86, 89] show that the NHE involves selective activation of the ST rather than the medial hamstrings as a whole and that the short head of BF is more heavily activated than the long head. T2 changes for individual muscles and each head of the BF are shown in Fig. 12.2. It should be noted that these T2 changes closely match the increases in muscle volumes when the NHE is employed in a training programme. Bourne and colleagues [67] have reported that 10 weeks of training with the Nordic exercise resulted in relatively selective volume increases of the ST, with moderate hypertrophy of the $BF_{SH}$ and small changes within the $BF_{LH}$ and SM (Table 12.1). These observations suggest

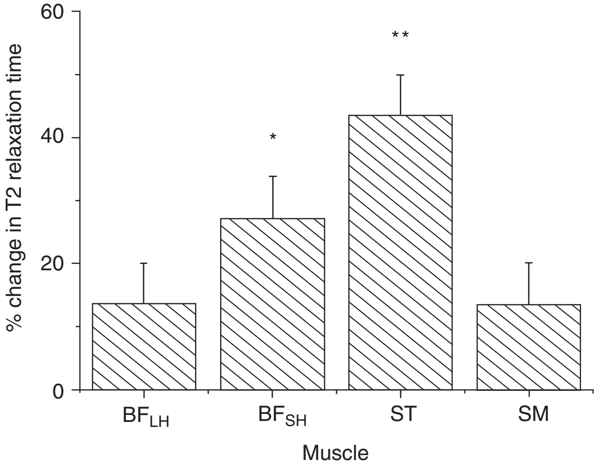

**Fig. 12.2** Muscle activation in the NHE as indicated by percentage changes in T2 relaxation times after 50 repetitions of the exercise performed by healthy recreational athletes. (From Bourne et al. [25] with permission.) ∗∗ST activation was higher than that of BF$_{LH}$ and SM. ∗BF$_{SH}$ activation was higher than BF$_{LH}$ and SM. Error bars depict standard errors. *BF$_{LH}$* biceps femoris long head, *BF$_{SH}$* biceps femoris short head, *ST* semitendinosus, *SM* semimembranosus

**Table 12.1** Effects of 10 weeks of progressively overloaded strength training on changes in hamstring muscle volumes and the proportional contribution to whole hamstring muscle volume change made by individual muscles or muscle segments

| Training exercise | Measure of hypertrophy | BF$_{LH}$ | BF$_{SH}$ | ST | SM |
|---|---|---|---|---|---|
| NHE | % Change in volume | 5.6 ± 5.9 | 15.2 ± 9.8 | 20.9 ± 11.3 | 4.9 ± 6.3 |
| | % Contribution to hamstring volume change | 14 | 21 | 52 | 13 |
| 45° hip extension | % Change in volume | 12.3 ± 7.0 | 8.4 ± 7.3 | 14.0 ± 8.4 | 10.4 ± 7.5 |
| | % Contribution to hamstring volume change | 29 | 10 | 33 | 28 |

From Bourne et al. [67]

that chronic training effects are also indicative of muscle activation patterns observed via fMRI.

### 12.4.1.3 Seated and Prone Leg Curl

Seated and prone leg curls elicit very high levels of BF and medial hamstring nEMG (>80% MVIC) [66, 87, 88]. As for the NHE, fMRI shows that the leg curl preferentially recruits the ST and, to a lesser extent, the short head of BF with lower levels of BF$_{LH}$ and SM activation [69, 86, 90]. Ono and colleagues [69] observed selective activation of the ST during an eccentric-only prone leg curl (120% 1RM) and during a conventional prone leg curl performed at 50% 1RM. Similarly, Mendiguchia and colleagues [90] reported preferential recruitment of the ST following eccentric prone leg curls performed at 120% 1RM. In this study, the T2 values in the ST, but not $BF_{LH}$ or SM, remained elevated 72 h after exercise, which suggests that only ST experienced significant damage [90]. More recently, Fernandez-Gonzalo and colleagues [86] reported greater T2 shifts in the ST (65%) and $BF_{SH}$ (51%) than the $BF_{LH}$ (14%) and SM (~4%, but not significant) during an inertial flywheel leg curl exercise.

#### 12.4.1.4 Supine Sliding Leg Curls

Two studies [88, 91], involving female athletes, reported very high levels of BF and medial hamstring nEMG (>100% MVIC) during the supine leg curl in which high-intensity loading is limited to the eccentric portion of the movement. In the first of these studies, Zebis and colleagues [88] observed significantly higher nEMG of BF than the medial hamstrings. More recently, Tsaklis and colleagues [91] observed no significant difference between the BF and medial hamstring nEMG in the same task. As far as we are aware, there have been no fMRI studies of this exercise, and it is not possible to state, definitively, which muscles are preferentially targeted in this movement (Fig. 12.3).

#### 12.4.1.5 Glute-Ham Raise

There are a number of variants of this exercise, and its intensity is altered by moving the footplate closer to or further from the semicircular knee/thigh pad. Placing the knees, rather than the thighs, on the padding makes the external moment arm longer and increases the exercise intensity. Bourne and colleagues [66] examined medial and lateral hamstring activation during the eccentric portion of the glute-ham raise exercise which was performed with a long external moment arm that prevented participants from completing the concentric portion of the movement. Like the NHE, the glute-ham raise involved relatively high levels of medial (~75–80% MVC) and lateral nEMG (~60% MVC) and therefore relatively selective medial hamstring activation (Fig. 12.4) [66].

**Fig. 12.3** The sliding leg curl. The sliding (eccentric phase) can be done with one or two limbs, and extra mass can be held on the hips

**Fig. 12.4** The glute-ham raise exercise

#### 12.4.1.6 Razor Curl

The razor curl, a relatively popular alternative to the NHE, involves simultaneous hip and knee extension. One variant of this exercise, performed from a glute-ham machine with the mid-thighs positioned over the padding at full knee and hip extension, has been examined in a sEMG study [92]. These authors observed greater activation of the medial (nEMG = 85%) than the lateral hamstrings (nEMG = 65%). van den Tillaar and colleagues [93] also observed higher medial than lateral hamstring involvement in the more conventional form of the exercise that was performed kneeling on a flat surface. These authors normalised the sEMG to that observed in sprint running, and this precludes a comparison of nEMG between these two razor curl studies (Fig. 12.5) [92, 93].

#### 12.4.1.7 Forty-Five Degree Hip Extension from Roman Chair

In a recent sEMG investigation of nine common hamstring exercises, Hegyi and colleagues [94] reported that the 45° hip extension exercise (with a 12RM load) was the only task to elicit greater nEMG activity of the $BF_{LH}$ than the ST. This is consistent with earlier work by Bourne and colleagues [66] who demonstrated that the 45° hip extension exercise involved the highest BF to medial hamstring sEMG ratio of ten common exercises. In both studies, participants performed the exercise with 12RM loads, and high absolute levels of BF (up to 75% MVIC) and

**Fig. 12.5** The razor curl

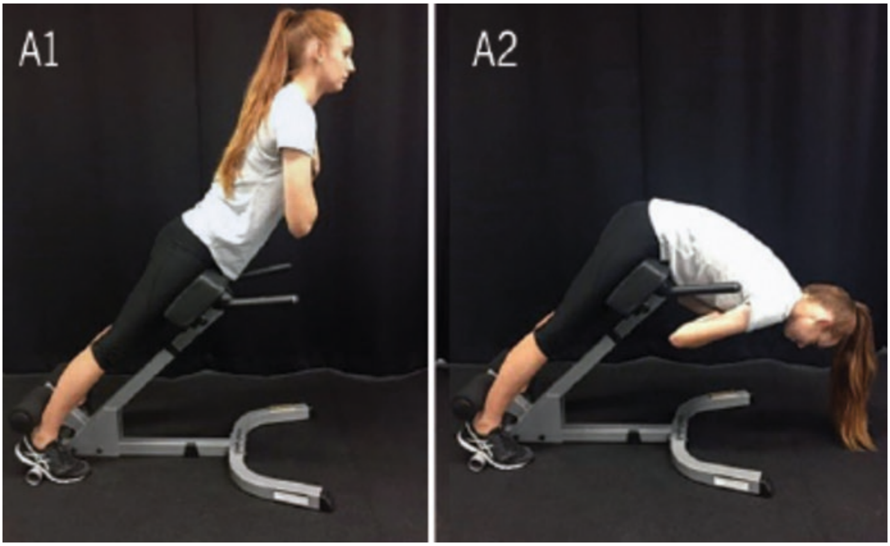

**Fig. 12.6** The 45° hip extension exercise. (From Messer et al. [89] with permission)

medial hamstring (up to 61% MVIC) nEMG were observed [66, 94]. Bourne and colleagues [66] also employed fMRI to map the spatial patterns of hamstring activity during this exercise. The results of this analysis revealed that the 45° hip extension exercise involved relatively uniform activation of the biarticular hamstrings and, as expected, modest recruitment of $BF_{SH}$. More recently, these fMRI observations have been corroborated in a cohort of recreationally active female athletes [89]. Both of these fMRI studies [66, 89] reported that the 45° hip extension exercise elicits a significantly higher $BF_{LH}$ to ST ratio than the NHE (Fig. 12.6).

Ten weeks of training with the 45° hip extension exercise elicits hamstring muscle volume changes [67] that closely match the acute T2 changes observed immediately after the exercise is performed [66] (Table 12.1). The changes in $BF_{LH}$ volume were significantly larger than those observed in another experimental group that performed the NHE over the same period [67].

#### 12.4.1.8 Stiff Leg Dead Lift and Romanian Dead Lift

Ono and colleagues [70] reported selective nEMG of the $BF_{LH}$ and SM relative to the ST during the eccentric and concentric phases of a stiff leg dead lift, while Zebis and colleagues [88] observed more selective sEMG activity of the medial than lateral hamstrings during a Romanian dead lift (RDL). McAllister and colleagues [95] have reported significantly higher $BF_{LH}$ nEMG in the eccentric RDL than the eccentric prone leg curl.

As far as we are aware, there are no published fMRI studies of the RDL. However, Ono and colleagues [70] have employed fMRI to map the T2 shifts immediately after and in the days following the performance of a stiff leg dead lift. Their analysis revealed a significant increase in T2 values of the SM, which exceeded the changes observed within $BF_{LH}$ and ST immediately after the exercise. This is, to our knowledge, the only observation of relatively selective activation of the SM over other hamstring muscles (Fig. 12.7).

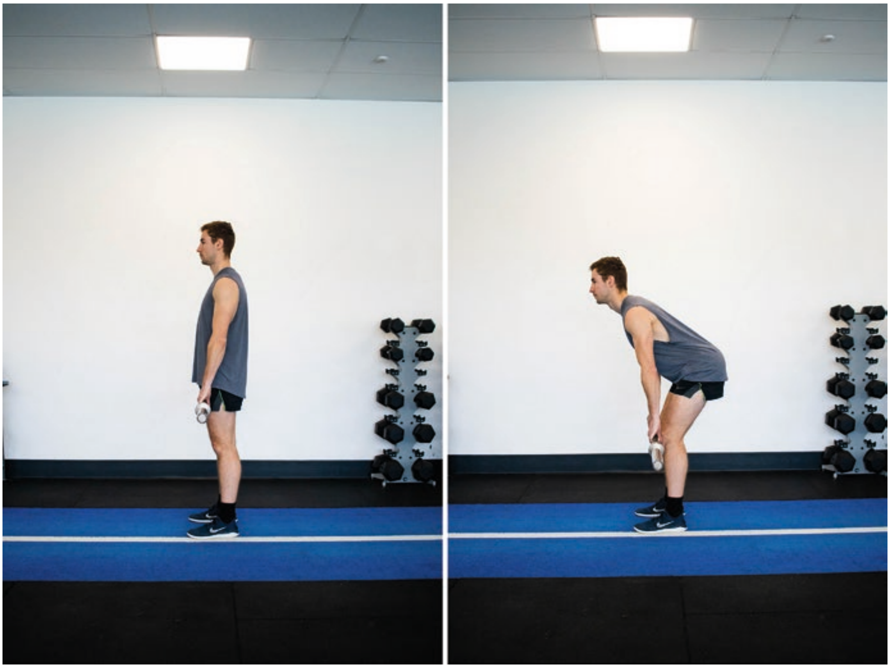

**Fig. 12.7** The Romanian dead lift

#### 12.4.1.9 Supine Bridges

The supine bridge exercise can be performed with varying degrees of knee flexion. The highest levels of hamstring nEMG have been observed when the exercise is performed with an extended knee, and this position typically results in relatively even EMG of the BF and medial hamstrings [66, 94]. These sEMG observations are in line with a recent fMRI study [65], which reported no significant difference in $BF_{LH}$ and ST activation during the straight-knee supine bridge. This study showed that $BF_{LH}$ was preferentially recruited over its short head and that the ST was significantly more active than the SM and $BF_{SH}$ [65]. When performed with the knee flexed (i.e. bent-knee bridge) rather than fully extended, the magnitude of hamstring nEMG is significantly reduced, and the exercise appears to more selectively recruit the medial hamstrings (Fig. 12.8) [66, 94].

#### 12.4.1.10 Good Morning Exercise

Recently, Hegyi and colleagues [94] demonstrated that the good morning exercise elicited the lowest levels of $BF_{LH}$ and ST nEMG of nine common hamstring exercises performed with a 12RM load. In this study, the medial hamstrings were more active than the BF in the eccentric, but not concentric, phase of the movement. These observations are in line with earlier work by McAllister and colleagues [95]

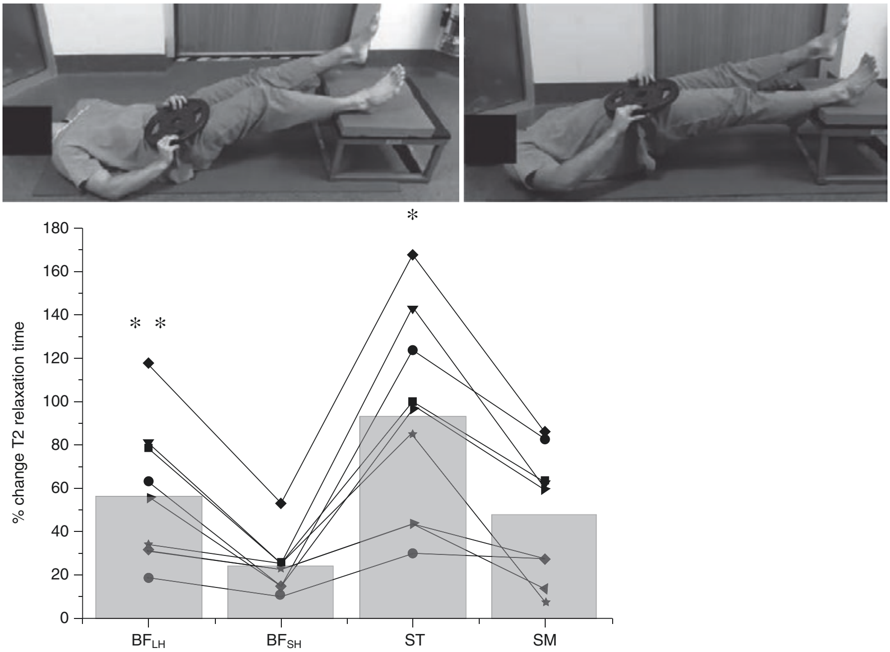

**Fig. 12.8** Top: the long-levered or straight-knee bridge exercise. Bottom: the T2 changes are shown to demonstrate the significant variation between individuals in the absolute size of this response. (From Bourne et al. [65] reproduced with permission)

**Fig. 12.9** The good morning exercise

who reported higher levels of medial than BF nEMG during the good morning exercise. The low levels of hamstring activation suggest that this exercise may rely relatively heavily upon other hip extensors, such as the gluteals and adductors (Fig. 12.9).

#### 12.4.1.11 Kettlebell Swing

There are several variations of kettlebell swings; however, most are performed explosively and with relatively light loads. A recent study by Del Monte and colleagues [96] reported significantly higher medial hamstring than BF nEMG during hip hinge, squat and double-knee extension kettlebell swings. In this study, the hip hinge exercise produced the greatest magnitude of hamstring sEMG of the three variants [96]. These observations are in line with earlier work from Zebis and colleagues [88], who reported that kettlebell swings resulted in the most selective activation of the medial hamstrings out of the 14 exercises examined in that study. We are unaware of any fMRI investigations of this exercise (Fig. 12.10).

#### 12.4.1.12 Hip Thrusts

The hip thrust is typically performed to target the synergists of the hamstrings at the hip, including the gluteus maximus (GM) and adductor magnus (AM). The exercise involves higher levels of GM than BF nEMG, and both these muscles

**Fig. 12.10** The kettlebell swing exercise

**Fig. 12.11** The hip thrust exercise

appear to be more active in the hip thrust than in a squat with similar relative loads (10RM) [97]. The hip thrust has also been reported to involve higher levels of GM activity and lower levels of BF activity than the conventional barbell dead lift [98]. As far as we are aware, fMRI techniques have not been employed to assess the muscle activation patterns of the hip thrust (Fig. 12.11).

#### 12.4.1.13 Squats, Leg Press and Lunges

Squats, leg press and lunges all involve simultaneous hip and knee extension with similar ranges of movement at the hip and knee joints. As a consequence, they do not involve significant hamstring (or rectus femoris) length changes. For example, Jonhagen and colleagues [99] have reported that there is no significant active hamstring lengthening (eccentric action) in either the walking or jumping lunge variants.

Surface EMG studies of the hamstrings during squats have reported widely discrepant levels of muscle activity (30–80% MVIC) [100, 101] possibly due to differences in electrode placement and crosstalk from other muscles. Functional MRI suggests that the hamstrings contribute very little during this exercise. In 1995, Ploutz-Snyder and colleagues [102] reported no significant T2 changes within the hamstrings after a conventional bilateral squat protocol involving six sets of ten repetitions with ~10RM loads performed by strength-trained men. These results were corroborated by observations of acute muscle swelling (increases in anatomical cross-sectional areas driven by fluid shifts into active muscles), which was limited to the vastii muscles and the adductors [102]. These fMRI results have now been replicated at least three times, most recently by Illera-Domínguez and colleagues [103], who observed no significant T2 increase in any of the hamstrings immediately after a flywheel-resisted squat training session. Together, these data suggest that the conventional squatting exercises are poor activators of the hamstrings regardless of whether barbells or flywheels act as the external resistances.

It is worth considering that many strength and conditioning coaches believe the hamstrings to be important contributors in the squat. Indeed, there are a number of influential leaders in the powerlifting community who advocate certain squatting techniques on the basis of their presumed ability to make better use of the hamstrings. Some athletes also mistake adductor muscle soreness in the days after squatting as evidence for hamstring involvement. Advocates for exercises with a proven ability to significantly activate the hamstrings may need to employ a significant education component to counter the view that the needs of the hamstrings are well addressed with squats.

The leg press, like the squat, involves simultaneous hip and knee extension, and these two exercises involve similar thigh muscle activation patterns. Enocson and colleagues [104] have reported no changes in the hamstring fMRI signal intensity after submaximal and maximal leg press (50%, 75% and 100% of the maximum load that can be lifted in five sets of ten repetitions) efforts performed by strength-trained men. In fact, the hamstrings fMRI signal intensity changes after leg press were almost identical to those observed after the leg extension exercise in which these muscles are antagonists [104]. Similar results have been observed with a leg press against a flywheel resistance [105].

Very low levels of BF and medial hamstring nEMG (~<20% MVIC) have been observed during lunges, even when relatively heavy loads are employed, although the exercise may selectively activate the BF [66]. An fMRI study of professional soccer players [90] reported an elevated T2 value in a single proximal slice of the $BF_{LH}$ immediately following a session of body weight lunges;

however, in the same study, there were no statistically significant T2 changes in the remaining seven slices of the same muscle. While these data might be interpreted as evidence that lunges are effective in targeting the $BF_{LH}$, particularly at its proximal end, the very low nEMG amplitudes suggest that the exercise likely provides a suboptimal stimulus for improving strength or evoking adaptations in this muscle. As noted previously, there appears to be little or no active hamstring lengthening in at least two variants of the forward lunge [99], and this brings into question claims that these exercises are good alternatives to those with a proven capacity to change hamstring muscle size, architecture and strength.

The limited hamstring activity in the squat, leg press and lunge does not imply that these exercises will have no value in athlete preparation or in hamstring injury prevention. These movements involve significant activation of other hip extensors, including the GM and the adductors (particularly AM), and these muscles may ‘protect’ the hamstrings from excessive strain during high-speed running [106]. Furthermore, numerous studies have reported correlations between squat strength and 5–40 m sprint performance [107–109], while others have shown that squat training results in improvements in short sprint performance (e.g. [110]).

### 12.4.2 Functional or Effective?

It is often argued that exercises performed in training should, whenever possible, closely resemble the movement patterns performed in competition because this should maximise the ‘transfer’ of benefits. Many use the term ‘functional’ to describe such exercises, despite the fact that it is not well-defined. Some devotees of functional exercise also argue, despite level 1 evidence to the contrary, that the NHE will be relatively ineffective at reducing injury rates because the exercise is not sufficiently specific to high-speed running. This argument completely ignores the role of structural factors (muscle and tendon adaptations) that also have the potential to influence injury susceptibility. Exercises that isolate the hamstrings have a proven capacity to alter muscle architecture [67, 111–117], change the expression of collagen at the muscle-tendon junction [118] and stimulate substantial and selective hypertrophy [67], and these and other adaptations may reduce injury risk. It might therefore be said that these hamstring exercises are structural and, we argue, that structure also matters! The idea that exercises must be specific to running (in terms of posture, movement velocity, laterality and ROM) to be effective in preventing injury is clearly not supported by the evidence at hand [119–121]. Furthermore, very few appear to fully understand the significant limitations of the research that has examined the concepts of specificity. Typically, these studies have explored the impact of training method X on the performance of another task (task Y) such as a vertical jump or 30 m sprint over a period of 6–12 weeks in previously untrained people or recreational-level athletes. The brevity of these interventions limits the contribution of structural adaptations and exaggerates the role of neural factors, particularly improved coordination and technique, which are extremely task specific. Furthermore, these studies almost never combine training methods (e.g. method X plus sprint training), and the impact of the combination is not observed. In contrast, athletes always combine multiple training methods and train for many months of the year.

It must be acknowledged, however, that as yet untested exercise interventions involving different exercises or high-speed sprinting may one day prove to be equally or more effective than those previously examined. Furthermore, even if alternative interventions are less effective in RCTs, they may end up having a more positive effect on injury rates in sport if they are more widely adopted [122]. At the time of writing, however, the level 1 evidence for injury prevention is limited to isolated knee flexor exercises [119–121, 123]. Future work, examining the impact of alternative exercises (or combinations of exercises) and additional high-speed running, seems warranted.

### 12.4.3 Exercise Selection for Hamstring Rehabilitation

So how might current findings be used after the RTS? As the previously injured $BF_{LH}$ may be atrophied many months after the RTS [13], it might be advantageous to employ a 45° Roman chair hip extension exercise (or similar) to counter this. Stretch-related hamstring tears seem to selectively impact the SM [124], and these typically take a long time to recover [124, 125]. The limited evidence at hand suggests that the stiff leg dead lift may be a particularly appropriate exercise to target this muscle [70]. Indeed, the study of the stiff leg dead lift by Ono and colleagues [70] is, to our knowledge, the only one in which the SM is reported to be more active than the other hamstrings.

We should also consider the possibility that targeting one or more of the hamstring muscles might reduce the injury risk to others. A case has been made that a high relative reliance upon or ‘use’ of the ST protects against hamstring strains [126], which predominantly occur within the BF muscle. Unfortunately, we do not yet know how to alter the relative reliance upon different heads of the hamstrings, although we do know that the ST is selectively targeted with knee flexion exercises [66, 67, 86, 89], and these have already been shown to significantly reduce hamstring injury rates [119–121, 123].

As discussed in Chap. 5, the potential role of the GM and AM muscles in hamstring injury prevention has been recognised [61, 106]. Modelling of sprint running suggests that if these hamstring synergists are poorly activated in the late swing phase of gait, the $BF_{LH}$ will experience higher than typical strains [106]. These findings support the argument that training should have a broader focus than hamstring exercises. For example, movements such as the barbell hip thrust and short- and long-lever bridges have been employed by Mendiguchia and colleagues [127] in their rehabilitation RCT, and these seem to be logical inclusions in an ongoing strength programme. Further work is required to determine the effectiveness of specific hip extensor exercise interventions on hamstring injury rates.

### 12.4.4 Strength Deficits

The optimal methods for reversing deficits in voluntary hamstring activation and strength after HSI are not known. However, it has been proposed that high-intensity resistance training, particularly with an eccentric emphasis, is likely appropriate [23] because of its powerful positive effects on voluntary muscle activation, hamstring fascicle length [67, 112–114] and injury recurrence rates [120, 121]. It is also worth noting that many of the successful published rehabilitation programmes in recent years have a significant component of eccentric hamstring strength training [125, 127–130] and an emphasis, at some stage in their progressions, on exercises performed at relatively long hamstring muscle lengths [127, 128, 130]. As a consequence, a continued emphasis on eccentric hamstring strength, as a part of a multifaceted sport-specific fitness programme [131] appears sensible.

### 12.4.5 Contraction Mode Emphasis

The injury prevention benefits of eccentric hamstring training are well-evidenced, although the RCTs in this arena have been largely limited to the NHE [120, 121] (see Chap. 6). The clinical utility of the Nordic exercise is significant because no equipment is required for its implementation; however, there is a deficit of evidence regarding alternative exercises and different approaches to injury prevention and RTS after injury. It has recently been argued that hamstring exercises need not be eccentric for them to be of benefit in injury prevention programmes [132, 133]. Van Hooren and Bosch [132, 133] suggest that high-intensity isometric strength training may be of equal or even greater benefit, although there are currently no isometric intervention studies to support this claim. Given the increasing use of isometric methods in sport, there is a pressing need to establish their impact on injury risk and athletic performance. It should also be acknowledged that conventional resistance training, involving mostly concentric and eccentric actions, will form the mainstay of resistance training programmes for most athletes. Furthermore, when significant excursions (long hamstring lengths) are involved, conventional hip extension strength exercise does stimulate increases in eccentric strength and $BF_{LH}$ fascicle lengths [67]. These findings suggest the possibility that purely eccentric or eccentrically biased strength training [120, 121, 123] may not be the only beneficial options available. However, at the time of writing, these are the only approaches with a strong evidence base.

## 12.5 Conclusion

Persistent deficits in horizontal ground reaction forces and repeated sprint performance suggest that there may be value in monitoring these parameters and addressing them in a sport-specific manner after hamstring injury. Neuromuscular deficits such as reduced voluntary activation and eccentric strength and short hamstring muscle fascicles are, arguably, well-addressed by sport-specific fitness programmes which include heavily loaded hip extensor and knee flexor exercises. There is now significant evidence showing how different exercises can target individual hamstring muscles and their synergists at the hip. Eccentrically biased (the NHE and flywheel leg curl) and conventional strengthening exercises (Roman chair hip extension and RDL) that involve the hamstrings being loaded at long lengths are likely beneficial.

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