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REVIEW ARTICLE

Hamstring Injury Prevention Practices in Elite Sport: Evidence for Eccentric Strength vs. Lumbo-Pelvic Training

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Abstract Hamstring strain injuries are endemic in running-based sports. Given the economic and performance implications of these injuries, a significant body of research has emerged in recent years in an attempt to identify risk factors and develop or optimise injury prevention strategies. Surveys of injury prevention practices among medical and conditioning staff in elite sport suggest that many sporting clubs invest significant efforts in eccentric hamstring conditioning and lumbo-pelvic or trunk stability programmes. The purpose of this narrative review was to critically evaluate the evidence underpinning these practices. Single-exercise eccentric training interventions have proven effective in the prevention of primary and recurrent hamstring strains, when compliance is adequate. However, despite its almost universal acceptance, the authors are aware of only one, very recent, prospective risk factor study examining the effect of lumbo-pelvic motion during sprinting on hamstring injury risk. Furthermore, the interventions exploring the effect of lumbo-pelvic training on hamstring injury rates have not measured stability in any way. An improved understanding of the evidence underpinning commonly employed hamstring injury prevention practices may enable clinicians and coaches to better prioritise effective strategies in the increasingly complex environment of elite sport.

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Key Points

- Elite sporting clubs invest significant efforts in eccentric hamstring and lumbo-pelvic conditioning programmes for the prevention of primary and recurrent hamstring injuries.
- Eccentric-only or eccentrically biased exercise interventions appear to be effective in reducing hamstring injury rates, but only when compliance is adequate.
- Despite the widespread acceptance in elite sport that lumbo-pelvic stability is an important and modifiable risk factor for hamstring injury, there is only modest scientific evidence for this belief and evidence regarding the efficacy of the commonly recommended exercises is absent.

1 Introduction

Hamstring strain injuries are a significant burden in sports that involve high-speed running [1–4]. In elite Australian Rules football, for example, hamstring strains account for one in six injuries [2], result in 20–21 missed matches per club in each 22-game season [2] and clubs pay approximately Australian $24,6000 a year in wages to players who are unable to take the field [5]. This financial impost does not take into account the significant costs involved in imaging and treatment. In other running-based sports such as track and field, hamstring injuries account for 75% of all lower limb strains [1], while in soccer [3, 6] and rugby union [7, 8], these injuries represent the most common cause of lost playing and training time at the elite level.

There has been significant research interest in hamstring injuries in recent years and this has led to the development of new concepts and practices in injury prevention [9–12] and rehabilitation [13–17]. Unfortunately, it is not clear whether these research findings have had a significant impact on primary hamstring injury and recurrence rates in elite sport [2, 18, 19]. Hamstring injury incidence in the Australian Football League appears to have declined slightly since 2011, while there has been a longer term trend for a reduction in injury recurrence [2]. It is not clear, however, whether these trends are the result of rule changes (reducing the number of interchanges) and more conservative approaches to return to play as opposed to improvements in prevention and rehabilitation programmes [2]. Observations from UEFA's Champions League soccer suggest that total hamstring injuries per 1000 h of exposure have increased by 2.3% per year over the past 13 years [19].

Perhaps our improved understanding is only just keeping up with increases in training volumes and intensities that predispose athletes to risk? For example, in the Champions League soccer competition, 70% of hamstring injuries occur during high-speed running [20], and players are now exposed to 30% more high-speed running than they were in 2007 [21]. Alternatively, it is possible that research interventions that are successful in sub-elite sport [11, 12] are either ineffective or simply very difficult to implement in the more complex environment of elite sport [22, 23].

Surveys of injury prevention practices in elite sport suggest that many sporting clubs invest significant efforts in eccentric hamstring conditioning and lumbo-pelvic or trunk stability programmes [24–26]. The purpose of this narrative review was to critically evaluate and contrast the evidence underpinning these practices.

2 Methods

While this review is narrative in nature, systematic searches were conducted via AMED, MEDLINE, CINAHL, PubMed, SPORTDiscus, EMBASE and the Cochrane Library from inception to July 2017 to ensure relevant research was not overlooked. Studies were required to be peer reviewed, in full text, in English language and involve human participants. The keywords for the search for risk factors were (Hamstring* OR biceps femoris OR semitendinosus OR semimembranosus OR posterior thigh) AND (tear OR strain OR injur*) AND (risk OR risk factor* OR caus* OR pred*). The search for papers relating to lumbo-pelvic motion or stability employed the keywords (Hamstring* OR biceps femoris OR semitendinosus OR semimembranosus OR posterior thigh) AND (tear OR strain OR injur*) AND (core OR stabil* OR control OR pelvi* OR lumb* OR kinematic*), while a search for papers relating to strength and eccentric employed the keywords (Hamstring* OR biceps femoris OR semitendinosus OR semimembranosus OR posterior thigh) AND (tear OR strain OR injur*) AND (strength* OR eccentric). The titles and abstracts of the resulting papers were examined by one author (AJS).

3 Hamstring Injury Prevention Practices and Beliefs in Elite Sport

Progress in the body of published research and the development of successful interventions in recreational and sub-elite sport must influence the beliefs and practices of those at the elite level before these can have any chance of reducing injury rates in that environment [23]. It must also be considered that some research findings from outside elite sport are not applicable in that setting and that research is open to misinterpretation and may therefore be misapplied.

A small number of published papers [24, 25] and unpublished reports [26] have examined the hamstring conditioning practices and beliefs of experts who work in elite sport. Additionally, there are a few published anecdotal reports of injury prevention or rehabilitation programmes that have been attempted at a single-team [27] or single-athlete level [28]. Together, these sources suggest that elite sports conditioning staff invest very significant efforts in eccentric hamstring conditioning and lumbo-pelvic conditioning programmes [24, 25, 28].

A predominantly e-mail survey of 44 'premier' league soccer clubs from the UK, Europe, Argentina, Australia, Canada and USA reported that the terms 'eccentric', 'eccentric hamstring', 'Nordic' and 'core' described the most effective 'exercises' in injury prevention programmes [24]. An unpublished report on injury prevention practices in the Australian Football League by Pizzari and colleagues [26] suggests that conditioning and medical staff at the elite level of Australian Rules football almost unanimously agree that eccentric hamstring and core stability exercises are amongst the most important means of preventing hamstring strain injury. More recently, Donaldson and colleagues [25] employed a Delphi consultation process to obtain an expert consensus as to what exercises and exercise progressions should be included in a lower limb injury prevention programme for community-level Australian

Rules football. Members of the Australian Football League Medical Officers, Physiotherapists and Sports Science Associations, along with a small number of clinicians and researchers, were invited to participate in the process and 55 contributed in at least one of the three Delphi rounds. The inclusions of the eccentric Nordic hamstring exercise (NHE) and a side plank (bridge) were agreed to by >75% of respondents in round one of the process.

The studies cited above also reveal that several other injury prevention practices, such as balance and proprioception training and adductor muscle strengthening, are considered important in elite team environments [24, 25]. However, the need for skills and fitness sessions and the many beliefs about what should be included in injury prevention programmes make for crowded weekly training schedules [29] in which effective injury prevention practices may be under-used [22]. This crowding is exacerbated in-season when there may be two games per week in elite European soccer [30] and the need for extended recovery from the heavier impacts of Australian Rules football and rugby. However, the evidence base for a number of these injury prevention practices is questionable. For example, there is no scientific evidence that gluteal activation exercises prevent injuries in sport but these are considered important by many in elite soccer [24]. It is also argued here, that despite their almost universal acceptance, there is very little scientific evidence that conventional lumbo-pelvic exercises help to reduce hamstring strain injury.

3.1 Defining Core or Lumbo-Pelvic Stability

According to one suggested definition, core stability is “the ability of passive and active stabilisers in the lumbo-pelvic region to maintain appropriate trunk and hip posture, balance and control during both static and dynamic movement” [31]. Another proposed definition is “the ability to control the position and motion of the trunk over the pelvis to allow optimum production, transfer and control of force and motion to the terminal segment in integrated athletic activities” [32]. The problem with these [31, 32] and numerous other definitions of lumbo-pelvic stability [33] is that they involve subjective judgements as to what is ‘appropriate’ or ‘optimal’ and thereby render the parameter unmeasurable. A slightly less ambiguous definition is that lumbo-pelvic stability is “the ability of the lumbopelvic-hip complex to return to equilibrium following a perturbation without buckling of the vertebral column” [34]. Definitions also vary significantly in terms of the anatomy that they cover. Some refer only to the stability of the ‘spine’ [35], while others refer also to the trunk, hips and/or pelvis [31, 32, 36]. The use of the term ‘core’ seems wholly inappropriate when less ambiguous anatomical terminology is readily available.

Despite frequent use of the term ‘stability’ in the exercise science literature, it is rarely measured. Instead, researchers are content to measure a range of factors that are argued to contribute to stability and there is general recognition that there is no gold standard in this domain [32]. Some of the tests employed are of static trunk and hip muscle endurance (e.g. Sorensen test [37] and side bridge holds to muscular failure), while others are said to assess dynamic stability (e.g. the Sahrmann test, which requires participants to prevent anterior pelvic tilt during a range of progressively more challenging lower limb movements while lying prone) or dynamic postural stability (e.g. Star excursion balance test) [35]. Alternatively, ‘stability’ may be judged by subjective assessments of movement patterns and posture during tasks such as single-leg squats, lateral trunk flexion and trunk rotation in unilateral stance and abdominal bridge [32], although these have been shown to have poor inter- and intra-tester reliability [38]. Surely stability, when used in reference to the control of lumbo-pelvic motion, is an entirely inappropriate term, particularly when only strength, endurance or balance are measured?

4 Theoretical Basis for Each Intervention

4.1 Lumbo-Pelvic Training

While none of the above definitions or tests appear suited to the investigation of hamstring strains, a theoretical role for aberrant pelvic motion in hamstring injury has been proposed by Chumanov and colleagues [39] via biomechanical modelling. Small increases in hip flexor activation, above those typically observed in high-speed running, were shown to increase the stretch experienced by the contralateral biceps femoris and other hamstring muscles during the late swing phase of gait [39]. The potential contribution of aberrant pelvic movement to hamstring strains appears logical given that this phase of gait has been associated with injury in high-speed running [40] and because there are well-understood relationships between muscle strain and muscle damage [41] and injury [42].

4.2 Eccentric Strength Training

Weakly activated and fatigued animal muscle-tendon units undergoing stretch have been reported to absorb less energy before failure than partially activated and fatigued ones [41, 43]. Weak hamstring muscles may therefore be more likely to experience damage than stronger muscles during active lengthening. Eccentric conditioning may also provide benefits in the form of improved damage resistance of the trained hamstrings [44]. This repeated bout effect

[45] may be mediated, at least in part, by the addition of in-series sarcomeres, as has been shown in rats after downhill running training [46, 47]. This adaptation is proposed to reduce the over-lengthening of sarcomeres during subsequent eccentric exercise [44, 48, 49]. While it is likely a mistake to suggest that damage resistance is brought about only by changes in fascicle lengths, it has recently been shown that professional soccer players with shorter biceps femoris long head (BFLH) fascicles are 4.1-fold more likely to sustain a future hamstring strain injury than those with longer fascicles [50]. Knee-flexor strength training involving the NHE, leg curls and hip extensions has also been shown to alter collagen expression in the endomysium of muscle fibres at the musculo-tendinous junction of the semitendinosus and these adaptations may also protect the hamstring muscles from strain injury [51].

5 Prospective Risk Factor Studies

5.1 Effect of Lumbo-Pelvic Motion on Hamstring Strain Injury

Given the widespread belief in the value of lumbo-pelvic exercises [24–26], one might presume that there is a significant quantity of research to substantiate a role for this parameter in hamstring injury aetiology. However, lumbo-pelvic motion has not been measured [52] in either of the commonly cited stability intervention studies of hamstring injury [15, 53]; thus, there has been, until very recently, no evidence to validate the claim that athletes with poor stability or motor control of the lumbo-pelvic region are more injury prone than their more stable counterparts. Schuermans and colleagues [54], however, have recently published a small prospective study that showed that four soccer players who went on to sustain hamstring strain injuries during an 18-month follow-up had previously exhibited greater anterior pelvic tilt and lateral flexion of the trunk during the airborne phase of sprint gait than 25 players who did not sustain injury. This study provides the strongest evidence that lumbo-pelvic motion or position may be a factor in hamstring injury; however, given the small sample, more work will be required to confirm this. A retrospective arm of the same study showed no differences in lumbo-pelvic positions or trunk motion between athletes with and without a history of hamstring strain injury [54].

Schuermans and colleagues [55] have also recently reported that amateur male soccer players with higher levels of normalised gluteus maximus surface electromyography activity in the hip flexion phase of maximal sprinting and higher levels of oblique abdominal electromyography activity in the hip extension phase were less likely to sustain subsequent hamstring injury than players with lower levels of muscle activation. While no measures of movement or movement variability were involved in this study, these results are consistent with the argument that greater control of the lumbo-pelvic region may reduce hamstring injury rates. Another small-scale prospective study by Franettovich-Smith and colleagues [56] has reported that 17 Australian Rules footballers who subsequently did not sustain hamstring injuries displayed lower levels of gluteus medius surface electromyography activity during submaximal treadmill running (at 12 and 15 km.h^{-1}) than nine players who did go on to sustain injury. In this study, gluteus maximus muscle activity was not significantly different between subsequently injured and uninjured players but there were effect sizes of 0.7 and 0.5 for running at 12 and 15 km.h^{-1}, respectively, for higher levels of gluteus maximus activity and larger gluteus medius and maximus muscle volumes (effect sizes of 0.7 and 0.6, respectively) in players who subsequently sustained hamstring injury [56].

There are studies that have explored the role of trunk and hip muscle strength and endurance in lower limb injury [57–59] and it has been argued that these parameters influence lumbo-pelvic stability. For example, Leetun and colleagues [57] showed that amongst a range of hip strength and trunk muscle endurance tests, high levels of external hip rotation and abduction strength appeared to protect basketball and track athletes from lower limb injury. Using a more satisfactory measure of stability, Zazulak and colleagues [59] showed that the amount of trunk displacement after sudden force release (via removal of a cable attached to a chest harness while in a semi-seated position) was related to subsequent knee injuries in female but not male collegiate athletes.

5.2 Effect of Eccentric Knee Flexor Strength on Hamstring Strain Injury

A number of prospective studies have examined the effects of eccentric and concentric knee flexor strength on hamstring injury rates in sport with mixed results [50, 60–67]. In the most adequately powered of these studies, involving 190 hamstring injuries, van Dyk and colleagues [65] assessed concentric quadriceps and eccentric hamstring strength in 614 professional soccer players over a 4-year period. In this study, both low concentric quadriceps [odds ratio 1.41; 95% confidence interval (CI) 1.03–1.92] and low eccentric knee flexor strength (odds ratio 1.37; 95% CI 1.01–1.85) were independently associated with an increased risk of hamstring injury. However, the absolute strength differences between subsequently injured and uninjured limbs were very small (Cohen's $d < 0.2$), suggesting that these strength variables are weak risk factors for hamstring injury.

In an earlier prospective study of 462 professional French, Belgian and Brazilian soccer players [62] involving 35 hamstring strain injuries, those with isokinetic 'strength imbalances' were 4.66 (95% CI 2.01–10.8) times more likely to sustain severe hamstring strain injury (>28 days recovery) than those without such imbalances. In this study, strength imbalance was defined as >15% between-limb differences in either concentric or eccentric strength or hamstring-to-quadriceps ratios of less than ~ 0.46 for concentric tests and ~ 0.85 for an eccentric hamstring-to-concentric quadriceps ratio. While this mixture of concentric and eccentric tests prevents firm conclusions regarding the predictive value of either contraction mode, the eccentric measures identified many more players with strength imbalances than did concentric ones [62]. Amongst another cohort of 100 professional soccer players, between-limb imbalances in isokinetic eccentric strength of ≥15% were associated with a significantly greater risk of hamstring strain (odds ratio = 3.88; 95% CI 1.13–13.23) [63]. In a much smaller prospective injury study of 30 track and field sprinters, six subsequently injured limbs were significantly weaker in knee flexion than the contralateral limbs when knee flexor torque was measured at $-60°\cdot s^{-1}$ but not at $-180°\cdot s^{-1}$ or $-300°\cdot s^{-1}$ [64]. In a similar isokinetic investigation of 44 competitive Chinese sprinters [68], eight hamstring strain injuries were observed and a concentric hamstring-to-quadriceps peak torque ratio of <0.6 at $180°\cdot s^{-1}$ was found to increase the risk of hamstring injury 17-fold.

In contrast to the aforementioned findings, some authors have reported no relationship between isokinetic measures of hamstring strength and injury risk. For example, in a cohort of 102 elite Australian Rules footballers, Bennell and colleagues [60] found no association between concentric hamstring to quadriceps strength or eccentric hamstring to concentric quadriceps strength at any testing speed ($60°\cdot s^{-1}$, $-60°\cdot s^{-1}$, $180°\cdot s^{-1}$ and $-180°\cdot s^{-1}$). However, this study only captured a total of nine hamstring strain injuries, thus it was likely underpowered to detect small- to moderate-sized relationships [69]. In a much larger investigation involving 164 hamstring injuries in 1242 first-year National Football League players, Zvijac and colleagues [70] observed no difference between subsequently injured and uninjured limbs when comparing isokinetically derived measures of concentric quadriceps and hamstring strength at $60°\cdot s^{-1}$ or $300°\cdot s^{-1}$. However, this study did not measure eccentric strength in any way.

By quantifying eccentric knee flexor force during performance of the NHE, it has been shown that Australian Rules footballers with low levels of eccentric knee flexor strength (<279 N) in late pre-season were 4.3 (95% CI 1.7–11.0) times more likely than stronger players to sustain a hamstring strain in the subsequent season [66]. Similarly, professional soccer players who produced <337 N of eccentric knee flexor force in pre-season were 4.4-fold (95% CI 1.1–17.5) more likely to sustain a hamstring injury than stronger athletes [50]. However, in keeping with the inconsistencies noted in the prospective isokinetic studies, others have reported no relationship between Nordic eccentric strength and hamstring injury [67, 71], although an investigation in Australian rugby union revealed that a between- limb imbalance >15% was associated with injury [67].

6 Known Effects of Training Programmes

6.1 Lumbo-Pelvic Training

It is important to know whether the interventions suggested in the literature actually affect the parameters they are proposed to change. A small number of studies claim to have observed improvements in lumbo-pelvic stability as a consequence of training [35, 72, 73]. None have examined whether any form of training reduces the aberrant movement patterns that are likely associated with increased hamstring strains during running. Impellizeri and colleagues [72] reported that amateur football players employing the FIFA 11+ warm-up programme for 9 weeks experienced a significant improvement in a sitting balance test, compared with a control group. In a more recent study, Chuter and colleagues [35] reported improvements in measures claimed to be indicative of dynamic (Sahrmann test and the star excursion balance test) and static stability (side bridge, flexor and Sorenson tests) following a lumbo-pelvic strengthening programme. In this study [35], which excluded participants with normal Sahrmann test scores (>1), training consisted of 8 weeks of isometric abdominal exercises in stable and unstable positions, hip abduction and lunges with trunk twists. Other studies exploring the effect of similar trunk strength training programmes on dynamic performance measures have reported mixed results [73, 74]. Sandrey and Mitzel [73] reported improvements in the star excursion balance test following 6 weeks of stability and trunk strength-endurance training in high-school track and field athletes. However, Sato and Mokha [74] reported no improvement in this parameter following 6 weeks of trunk muscle training in competitive and recreational runners.

In light of the aforementioned findings, there is a pressing need to establish whether the lumbo-pelvic exercises currently employed in elite sport and in intervention studies actually change the way that athletes move in such a way as to safeguard the hamstrings. Exercises such as the side plank have been advocated by experts [25] but the authors are not aware of any training studies showing that this exercise is sufficiently intense to change movement patterns in athletes [75] or reduce hamstring injury rates. Indeed, the exercise seems well suited for early rehabilitation or for use in completely untrained people. Furthermore, it will not be sufficient to establish improvements in sitting balance [72], trunk muscle endurance [57] or performance in tasks like the star excursion balance test [35, 73] because none of these replicate the movement patterns or the postural demands of high-speed running. Three-dimensional motion analysis may one day be employed to show reduced variability in pelvic motion and hamstring lengthening after lumbo-pelvic training programmes, although it is likely that field tests of pelvic motion, possibly using wearable sensors, would allow larger scale studies to be carried out.

While high levels of anterior pelvic tilt and lateral trunk flexion have been associated with hamstring injury [54], it is not known whether these technical traits are caused by poor strength, motor control or running technique. If the deficiencies are in technique, it is possible that running re-education (technique coaching) may be more appropriate in prevention programmes than trunk muscle strength and endurance training.

6.2 Eccentric Hamstring Strength Training

The efficacy of eccentric training for increased strength and muscle mass is well known [76]. The contraction mode specificity of such training is generally thought to result in greater gains in eccentric than concentric strength [77, 78] and this has proven true for the knee flexors [79]. In keeping with these observations, Mjolsnes and colleagues [80] have reported 11% increases in both eccentric isokinetic knee flexor strength at $-60°\cdot s^{-1}$ and the functional hamstrings to quadriceps ratio after 10 weeks of NHE training in sub-elite male soccer players. In contrast, a control group, which performed the leg curl with minimal emphasis on the eccentric portion of the movement, exhibited no significant improvement in eccentric strength [80]. Others have since reported 15–21% increases in eccentric isokinetic knee flexor strength after 4–6 weeks of NHE training [81, 82].

Ten weeks of strength training with the NHE has recently been shown to induce a $\sim$ 27% increase in peak knee flexor forces during the exercise, along with a $\sim$ 21% increase in fascicle length (from $\sim$ 10.5 to 12.7 cm) in the BFLH [83]. Muscle volumes also increased by 4.1, 13.4, 18.2 and 3.9% for the BFLH, biceps femoris short head, semitendinosus and semimembranosus muscles, respectively [83]. Potier and colleagues [84] have reported a 34% increase in BFLH fascicle lengths after 8 weeks of eccentric leg curl training, while Timmins and colleagues [85] reported a 16% increase after 6 weeks of eccentric knee flexor training on an isokinetic dynamometer. Interestingly, in this last study [85], volume-matched concentric training on the same device led to an equivalent reduction in fascicle length.

It has been suggested that changes in in-series sarcomere numbers should alter the torque-joint angle (T-JA) relationship [86] and thereby shift the knee angle at which peak torque is observed. Accordingly, Brockett and colleagues [86] have reported a $7.7° \pm 2.1°$, shift in the peak of the knee flexor T-JA relationships towards longer muscle lengths for up to 8 days after a single session of 72 NHEs, while in a pilot study, 4 weeks of lower volume NHE training caused a shift in the same direction of $\sim$ 6.5° [87]. Three weeks (seven sessions) of eccentric stiff leg deadlifts and leg curls were shown to shift the peak torque by approximately 20° towards a more extended knee angle [88]. In this latter study, concentric training using the same exercises and ranges of motion was shown to shift the T-JA curve towards shorter muscle lengths [88].

The combined effects of strength increases and a shift in the T-JA relationship towards longer muscle lengths may profoundly increase the knee flexor torques and muscle forces that can be generated at longer muscle lengths. For example, after 3 weeks of eccentric training, improvements in isometric strength of $\sim$ 50% have been reported at the knee angle of 20° flexion compared with $\sim$ 20% increases at the 50° flexion [88]. These adaptations, along with aforementioned changes in collagen expression at the muscle-tendon junctions [51] may improve the hamstrings' capacity to tolerate high levels of stress and strain, such as those experienced in the terminal-swing phase of sprinting. Alternatively, longer hamstring fascicles themselves may mediate changes in knee flexor torque and the T-JA relationship and concurrently render muscles less prone to strain injury [50].

7 Intervention Studies

7.1 Lumbo-Pelvic Exercises

An influential paper by Sherry and Best [15] is arguably the most frequently cited as evidence for lumbo-pelvic or trunk stability intervention strategies targeting hamstring strain recurrence [89, 90]. In this study, a rehabilitation programme containing progressive agility and trunk exercises proposed to improve trunk stability (PATS) resulted in significantly fewer injury recurrences than one that emphasised strengthening and stretching. The PATS programme's agility exercises included sideways, forward, backward and grapevine stepping while the trunk exercises included prone, supine and side bridges, single leg windmill touches, trunk rotation and Theraband 'pull downs'. The strengthening and stretching exercises were initially isometric contractions and these were progressed to prone leg curls with ankle weights, foot catches and a standing unilateral hip extension with straight knees and TheraBand™ resistance [15].

In a systematic review and meta-analysis of lumbo-pelvic exercise interventions, Perrott and colleagues [91] have reported a significant reduction in lower limb muscle strain injury rates. However, with the exception of the Sherry and Best paper [15], none of the included studies reported on hamstring injury rates and in the studies that showed reductions in lower limb injuries generally, lumbo-pelvic strengthening exercises were either not employed or were not the only components of the interventions. A study by Pasanen and colleagues [92], for example, reported an effect in favour of their intervention, which included running agility and balance exercises along with lower limb and trunk strengthening exercises, including the NHE. As the NHE alone has proven effective in reducing hamstring injury rates [10–12], it is impossible to determine whether other elements of the intervention had any effect [92].

While multi-modal interventions provide models that can be adopted by practitioners, there is no way to know which exercises within these interventions are 'active ingredients'. Another issue arises from the labelling of intervention strategies. By calling interventions core or trunk stability programmes, the impression is given that changes in stability are responsible for subsequently reduced injury rates. However, trunk stability has not been quantified in any way after implementation of PATS training [15, 53], and as a consequence, it is not possible to conclude that improvements in stability or pelvic motion have occurred, much less that they have been responsible for reductions in injury recurrence. In this circumstance, alternative explanations are equally defensible. For example, the PATS programme includes a 'single leg windmill touch', which involves an Arabesque style flexion of the hip over an almost fully extended knee. This exercise requires the hamstrings to act eccentrically and concentrically at long lengths and is similar (in terms of sagittal plane hip position and hamstring lengths) to the diver exercise, which has been employed as a part of the successful L-protocol in Askling and colleagues' rehabilitation studies [13, 14]. It seems reasonable to suggest that these exercises may have a significant positive impact on the architecture [83, 85], strength [93], T-JA relationship [88, 94] and damage resistance of the previously injured hamstrings, all of which could potentially mediate the relative success of the PATS intervention.

It should also be acknowledged that Sherry and Best's [15] PATS programme was originally compared with a stretching and strengthening programme that did not conform to currently accepted standards for hamstring rehabilitation. For example, the prone leg curl and the standing hip extension in the strengthening and stretching programme do not challenge the hamstrings at the longer lengths and at the intensities expected of late-stage rehabilitation [13, 14, 94, 95]. As a consequence, the PATS intervention may be flattered by its comparison to a poorly designed strength programme. Indeed, a subsequent study by the same group addressed this issue and has reported very similar results for the PATS programme and a strengthening and progressive running programme involving the NHE [53]. It should also be considered that a total of 26 recreational athletes have been treated with the PATS programme in the two studies that have reported its benefits [15, 53]. The effectiveness of this type of intervention in elite athletes is not currently known.

While not specific to hamstring injuries, Hides and Stanton [96] have reported on an injury prevention approach that emphasised motor control of the transverse abdominis and multifidis muscles and employed lower limb injuries as the outcome measure in elite Australian Rules footballers. Players were trained to voluntarily activate the multifidis and transverse abdominis muscles with the aid of feedback from ultrasound imaging. Exercises emphasised pelvic and lumbar spine posture, initially in non-weight-bearing positions and this was gradually progressed to upright weight-bearing tasks. While those players using the motor control approach were reported to be available for more games than a wait-listed control group, it should also be noted that the club at which this study was carried out sustained 12 hamstring injuries during the playing season [96] and this is significantly higher than the competition's average over the last two decades [2]. As a consequence, the intervention can hardly be said to have been successful in preventing hamstring strain injuries.

Despite apparently widespread belief to the contrary [24–26], there is a dearth of convincing evidence that lumbo-pelvic exercise can protect elite level athletes from primary hamstring strain injuries. Evidence for agility and trunk stability programmes in rehabilitation of recreational athletes exists, but there is no proof that the benefits arise from enhanced trunk stability and their effectiveness appears similar to a hamstring strength and running programme [53].

7.2 Eccentric Hamstring Strength Training

There is a growing body of evidence that eccentric knee flexor strength programmes reduce the risk of hamstring strain injury [10–14, 97] and most of these studies employed the NHE as the sole exercise in their intervention

[10–12, 97]. The first of the NHE studies involved 17–30 Icelandic and Norwegian soccer teams over four seasons [10]. After two seasons of baseline measurements, clubs were asked to employ the Mjolsnes et al. [80] 10-week strength protocol three times per week in the pre-season and once or twice each week in the two subsequent competitive seasons. Teams that elected to adopt the NHE reported 65% fewer hamstring strain injuries than those which declined to employ the exercise. More recently, Petersen and colleagues [11] conducted a cluster-randomised controlled trial in Danish sub-elite football, with the Mjolsnes et al. [80] programme assigned to 461 of 942 players who were followed for injury across a 12-month period. Players using the NHE experienced 3.8 compared with 13.1 hamstring strain injuries per 100 player seasons for controls. Even more impressively, the rate of recurrent injury in the invention group was 7.1 as compared with 45.8 hamstring injuries per 100 player seasons in the control group. Additionally, the number needed to treat to prevent a single injury recurrence was 3 (95% CI 2–6), which suggests the NHE is an extremely efficient intervention for hamstring rehabilitation [11]. Finally, using a similar cluster-randomised controlled trial, van der Horst and colleagues [12] allocated 20 amateur Dutch soccer teams ($n = 292$) to a 13-week, progressive intensity NHE programme while 20 teams ($n = 287$) served as a control. Players in the intervention group experienced a significant reduction in hamstring injuries compared with the control group (odds ratio, 0.3, 95% CI 0.1–0.7)

Two randomised NHE interventions reported no significant effect on hamstring injury rates [98, 99], although both reported very low compliance and one was not designed to increase knee flexor strength [99]. Engebretsen and colleagues [98] reported no benefits of the Mjolsnes et al. [80] NHE programme when it was assigned to first-, second- and third-division Norwegian soccer players deemed at high risk of hamstring strain injury, although only 21% of players assigned to the experimental group completed the minimum recommended number of training sessions. Gabbe and colleagues [99] also reported no significant benefits of NHE training on hamstring injury rates in community-level Australian Rules football. This study differs drastically from other NHE interventions in that it was designed to create a shift in the knee flexor T-JA relationship, so the exercise was performed only five times with 2-week intervals between sessions and a total of 72 repetitions was performed on each occasion. By contrast, the Mjolsnes et al. protocol [80] involves one training session with two sets of five repetitions in week 1 and builds to three sets of 8–10 repetitions on 3 days in the fifth week. As a consequence of these design features, the Gabbe et al. [99] protocol induced significant muscle soreness, which was cited as a reason for dropouts and only 47% of players completed two or more sessions and fewer than 10% of players completed all five.

Goode and colleagues [100], in a recent systematic review and meta-analysis of randomised controlled eccentric hamstring interventions, included three of the randomised NHE studies mentioned above [11, 98, 99] and one other small study that employed an eccentrically biased, flywheel leg curl exercise [101]. The results suggested that these eccentric interventions were not effective in reducing hamstring strains (relative risk 0.59, 95% CI 0.24–1.44); however, the authors noted that this estimate was imprecise, showed high heterogeneity and depended significantly on compliance rates. Participants who were compliant with their intervention programmes were significantly less likely to sustain a hamstring strain (relative risk, 0.35, 95% CI 0.23–0.55) than control participants and this estimate was precise and homogenous [100]. Furthermore, this meta-analysis was published before and therefore did not include the results of the study by van der Horst and colleagues, which strongly supported the NHE [12]. It can also be argued that the low-frequency NHE intervention study by Gabbe and colleagues [99], which contributed significantly to the heterogeneity in Goode et al. [100], should not have been included in a review that had the stated goal to “determine the effect of eccentric hamstring strengthening on the risk of hamstring injury”. Such low training frequencies are simply inconsistent with the aim of improving strength [102]. In interpreting these findings, it should be also considered that sub-elite athletes who must complete injury prevention sessions in their own time and in addition to their normal training commitment [98, 99] are far more likely to drop out of these programmes than are elite athletes who typically have these exercises built into compulsory and supervised squad training sessions. Thus, while intention-to-treat analyses are extremely relevant for sub-elite and community-based sport, the analysis of results for compliant participants may be of greater relevance to an elite environment.

Askling and colleagues’ [13, 14] ‘L-protocol’, which involves rehabilitation exercises that load the hamstrings at long length (the diver and glider), has been compared favourably to a ‘C-protocol’, which consists of ‘conventional’ exercises for the hamstrings performed at shorter muscle lengths with both eccentric and concentric phases. If properly performed, the L-protocol’s glider exercise involves only eccentric actions of hip extensor muscles, including the long hamstrings. In separate studies involving professional soccer players [13] and elite track and field athletes [14], the L-protocol resulted in an earlier return to sport (on average 23–37 days) and fewer recurrences than the C-protocol.

Together, the abovementioned studies provide an argument for the protective effects of eccentric or eccentrically biased hamstring exercises in primary injury prevention and rehabilitation programmes when their implementation is complied with. It should also be noted that several exercises are known to increase knee flexor strength [79, 83, 84, 88, 94], lengthen BFLH fascicles [83–85] and shift the T-JA relationship towards longer lengths [88]. While the active ingredient in single-exercise intervention programmes is easily determined, it is currently not clear whether increases in eccentric strength, as opposed to fascicle lengthening or changes in the expression of collagen at muscle-tendon junctions [51], is the most important adaptation. Given the lack of consistency in prospective studies of eccentric strength and hamstring strain injury, it is possible that the benefits of eccentric strength training may be mediated, at least partly, by adaptations other than improved strength.

8 Limitations

Clearly, our review is not without limitations. For example, our search was restricted to English language publications and this may have excluded studies of interest. Furthermore, this review did not involve a systematic evaluation of the methodological quality of the included studies. It should be noted, however, that such evaluations have been reported previously and the PEDro scores reported for eccentric or eccentrically biased knee flexor intervention studies [100] tend to be higher than those reported for studies of lumbo-pelvic interventions [91].

9 Conclusion

Despite the widespread acceptance in elite sport that lumbo-pelvic stability is an important and modifiable risk factor for hamstring injury [24–26], there is only a small amount of scientific evidence for this belief. Indeed, the authors are aware of only one small prospective risk factor study examining the effects of pelvic and trunk positions during sprinting on hamstring injury [54]. Furthermore, the frequently cited trunk stability interventions aimed at reducing hamstring injury recurrence [15, 53] have not actually measured trunk stability [52] and, as a consequence, neither of these studies has established that the benefits are not mediated via alternative mechanisms. Many of the interventions employing lumbo-pelvic and trunk exercises are multi-faceted, thus it is not possible to conclude which of their elements mediate the reported benefits. Adaptations within the hamstring muscles themselves have not been ruled out, thus even if trunk and hip muscle training can reduce lower limb strain injury or its recurrence [15], there seems no valid reason to claim that these benefits have arisen as a consequence of changes in trunk stability. Significant research is needed to establish that lumbo-pelvic exercises, particularly those performed at very low intensities such as side and front planks, are not occupying precious time in busy training schedules without justification [75].

There is mixed evidence from prospective studies to suggest that eccentric knee flexor strength protects against hamstring strain injuries [50, 60–67]. The evidence is more consistent for eccentric and eccentrically biased strength training interventions [10–14, 97–99], particularly when compliance rates are factored in [100]. It is possible that increases in hamstring fascicle lengths [51] may protect these muscles from strain injuries more than the changes in strength [65], and there is evidence that these adaptations occur as a consequence of eccentric knee flexor training [51, 83, 85]. At present, the evidence for eccentric knee flexor strength training is significantly stronger than that for lumbo-pelvic 'stability' training and there is no evidence that changes in stability or lumbo-pelvic movement patterns occur, much less protect against injury, as a consequence of the exercises that are currently advocated in the literature.

Compliance with Ethical Standards

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Conflict of interest Anthony J. Shield is a co-inventor of a device employed to assess eccentric knee flexor strength (PCT/AU2012/001041.2012) and is also a shareholder in a company responsible for commercialising the device. Matthew N. Bourne has no conflicts of interest directly relevant to the content of this review.

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