Hamstring Strain Injuries: Incidence, Mechanisms, Risk Factors and Training Recommendations

Abstract

Hamstring strain injury (HSI) is one of the most commonly reported sports injuries. This has led to a substantial amount of research aimed at identifying factors that increase the risk of an athlete suffering a HSI. The identification of risk factors allows practitioners to plan intervention programmes with the aim of reducing the rate and severity of HSI. As a multitude of factors contribute to the risk of HSI, interventions should be multifaceted in nature. This review outlines the incidence, mechanisms and risk factors for HSI and provides evidence-based training recommendations to reduce the rate and severity of HSI.

Key Words: Eccentric Strength; high-speed running; multi-faceted approach; prevention.

Introduction

Hamstring strain injuries (HSI) are one of the most commonly reported lower limb injuries, with high incidence and re-injury rates across a number of sports (12,16,26,29,31,76,77,79,102,114). These injuries can be viewed as acute (i.e., as a direct result of an impact or traumatic event with sudden feelings of pain), overuse (i.e., exposure to inappropriately high training load/volume over an extended period of time) and chronic or recurrent (i.e., the repeat injury of the same muscle site due to a reduction in function and/or lack of appropriate healing and rehabilitation, which may also take the form of an acute injury) (18). In some cases HSI can be severe in nature, which has been previously defined as an injury that takes greater than 28 days to recover (29). Often, HSI leads to a significant loss of athlete playing time which may have a detrimental effect upon team performance and subsequent financial losses for sporting organizations (41,44). A report in Australian football from the 2012 season, estimated that HSI could cost clubs up to $245,842 per season (44). This was seen as an increase of 71% in comparison to the figures reported for the 2003 season (44).

This has led to a substantial amount of research aimed at identifying risk factors that predispose athletes to suffering a HSI. These risk factors have been classified into two groups: modifiable and non-modifiable (56). The modifiable risk factors are those that can be altered through a training intervention and include: reduced eccentric strength, fatigue, flexibility, high-speed running loads and insufficient or inadequate warm up. However, despite identifying several risk factors that contribute to HSI risk, a substantial amount of research evaluating HSI prevention programmes have centred solely around the development of eccentric hamstring strength. These have often included the use of the Nordic hamstring curl (2,90,107). In some cases, interventions of this nature have reduced HSI by 65% (2), as well as significantly reducing the time lost to HSI (90).

Despite this ongoing research, and subsequent training recommendations, HSI have been reported to have increased annually within professional soccer (31), athletics (72) and in cricket (77) since the introduction of the 20 over format (a faster paced game played across 20-overs per team). Although challenging to fully explain, this may be due to the lack of emphasis placed upon the other modifiable risk factors within HSI prevention programmes. Furthermore, post-injury, the hamstrings not only appear to suffer from a loss of strength (25,50,54,64,73,74), but also flexibility as well (50,64), which is believed to contribute to the risk of re-injury. Therefore, it appears that additional factors, and not just eccentric hamstring strength alone, warrant particular attention within HSI prevention programmes. In order for these programmes to be successful, practitioners should have a thorough understanding of the different types of HSI, the injury mechanisms and the potential risk factors associated with HSI. Thus, the purpose of this review is to summarise the injury mechanisms, injury rate and risk factors on HSI, with a focus on providing evidence-based guidelines for multifaceted injury prevention programmes.

Throughout this review it is important to have an appreciation for different injury definitions used within the literature when comparing any research of this nature. For example, Orchard et al. (76) define an injury as one that causes an athlete to miss only match playing time. In contrast, Ekstrand et al. (29) includes any injury that prevents a player from taking part in training and competition. These differences in methodologies may have an influence over the prevalence and severity of reported HSI.

Hamstring Anatomy

Having an understanding of the basic hamstring anatomy and function can aid to improve the understanding of HSI risk. The hamstring muscle group consists of three major muscles of the posterior thigh: semitendinosus, semimembranosus and biceps femoris (long and short head) (18,108,113). The biceps femoris long head, semitendinosus and semimembranosus have a biarticular formation where they cross both the knee and hip joint. This biarticular formation causes the hamstring to stretch at two points, a factor often hypothesised to contribute to the high rate of HSI (114). The biceps femoris long head originates from the medial facet of the ischial tuberosity via its proximal tendon, and distally inserts to the lateral surface of the fibula head (18,108,113). The semitendinosus also originates at the ischial tuberosity before extending and inserting distally at the medial surface of the tibia (18,108,113). The semimembranosus proximal tendon arises from the lateral aspect of the ischial tuberosity and extends distally to attach at the posterior aspect of the medial tibial condyle (18,108,113). The biceps femoris short head arises from the femur and inserts at the fibula head, making it a uniarticular muscle that crosses only the knee joint (18,108,113). The isolated function of the hamstring muscle group is to shorten concentrically to produce knee flexion and hip extension. During more integrated or dynamic muscle actions (e.g., jumping, sprinting and changing direction), the hamstrings aid in the stabilization of the lumbo-pelvic hip complex and knee joints (51,86).

Of particular interest regarding HSI is the intramuscular or central tendon, which descends down the length of the muscle belly (17,55). The intramuscular (central) tendon acts as a supporting structure to which the muscle fibres attach (17). When this tendon is injured or damaged, the injury is considered to be more severe with increased return to training and competition (17,22,55,82). This is highlighted in the study by Comin et al. (22) who identified 45 biceps femoris injuries, of which 12 also involved the central tendon. It was reported that the recovery times for those injuries involving the central tendon that didn't require surgical intervention (71 days), were significantly ($p < 0.01$) longer than those not involving the central tendon (21 days) (22). Therefore, the intramuscular tendon has important implications for injury prevention and rehabilitation.

Functional Role of the Hamstrings in Athletic Performance

The predominant role of the hamstrings within sports performance is often centred around their function during high speed running. Their primary role during this is to decelerate knee extension during the terminal swing phase (a point in the running cycle where neither limb is in contact with the ground) so that the foot can make ground contact under the bodies centre of mass, following which they act as an active hip extensor (86,87). During the terminal swing phase the biceps femoris long head, semitendinosus and semimembranosus exhibit peak strain, produce peak force and perform greater negative energy absorption (86). It is a common theory that the additional work placed upon the hamstrings at this time point is responsible for the high number of HSI (21,86,87).

Furthermore, the hamstrings appear to play an important role in horizontal force production during acceleration sprint mechanics (68). It has been proposed that those athletes displaying higher levels of hip extensor torque (eccentric hamstring strength) and the highest hamstring electromyography (EMG) activation during the terminal swing phase were able to generate greater horizontal ground reaction forces (68). The important role of the hamstrings during running performance is further supported by Kyrolainen et al. (53) who suggested that as running speed increases, so too does force production, which can be partly attributed to the action of the hamstrings (53). Therefore, as the hamstrings appear to play a prominent role in speed development, it is essential for practitioners to have an understanding of appropriate training methods that optimize both their health and performance.

Hamstring Strain Injuries (HSI)

HSI are one of the most commonly reported sports injuries (12,16,18,26,29,31,76,77,79,102,114). A HSI is commonly classified as a grade I-III strain depending on its level of severity (18). A grade I strain typically effects a small number of muscle fibres, grade II a significant amount of muscle fibres and grade III a complete tear of the muscle (18). Using similar grade classifications, Ekstrand et al. (30) reported return to play times to be 17 ± 10 days (grade I), 22 ± 11 days (grade II) and 73 ± 60 days (grade III) within professional soccer. In more recent times, additional injury grading systems have been proposed in order to increase their specificity and provide clearer information on return to play times (20,69,81). Pollock et al. (81) suggest that alongside grading the injury severity on a scale of 1-4 (small, moderate, extensive or complete tear), an additional suffix of (myofascial, musculo-tendinous or intra-tendinous) should also be included to indicate the location of the injury. Similarly, Chan et al. (20) proposed a new classification system which included lesion site (proximal musculo-tendinous junction, muscle, or distal musculo-tendinous junction), with muscle injuries having two additional suffixes including location (proximal, middle, or distal) and anatomical site (intramuscular, myofascial, myofascial/perifascial, myotendinous, or combined). Including such information within injury classifications has been proposed to aid practitioners with both injury prevention and rehabilitation practices (20,69,81).

HSI Type

A type I strain is commonly referred to as a sprinting related strain and are typically reported in sports such as rugby, athletics and the various football codes (5,16,26,29,76,79,114). These often occur when the hamstring muscle group are required to work eccentrically (produce force whilst lengthening) in order to decelerate the limb and control knee extension during the terminal swing phase of high-speed running (21,42,57,88). This mechanism of injury has been supported by the work of Heiderscheit et al. (42) and Schache et al. (88) who studied the time frame of hamstring injury during running and concluded that injury occurred during the late swing phase. Schache et al. (88) further reported that during the injury phase, the biceps femoris reached a peak length estimated to be 12% greater than that seen during upright posture and exceed the normalized peak length of the medial hamstrings. Furthermore, Higashihara et al. (45) reported significant increases in hamstring activation when running speeds were increased from 85% to 95% of an individual's maximum velocity. Oftentimes, the biceps femoris is the main site of damage in type I strains, with Askling et al. (5) stating that the biceps femoris (long head) was the primary injury location in all 18 hamstring injuries suffered by elite level sprinters within their study. A further eight sprinters (44%) suffered additional injury, with seven at the semitendinosus and one at the biceps femoris short head (5).

Type II hamstring strains are commonly seen as stretch related injuries (18). These injuries most commonly occur during combined excessive stretching into hip flexion and knee extension (6). Askling et al. (6) report that these types of injury can occur in several sports (soccer, dance, judo, gymnastics, sprint running) and during different athletic actions (high kicking, stretching and sagittal and side splits). However, this is most commonly seen amongst dancers, with Askling et al. (3) reporting that 66% of acute HSI occurred during a sagittal plane split and 12% during a side split. These injuries commonly affect the semimembranosus, with Askling et al. (6) reporting this occurrence in 83% of type II strains, with all semimembranosus strains also involving its proximal free tendon. It is important for practitioners to understand which type of HSI is most likely to occur in their athletic population, enabling more specific rehabilitation protocols to be applied.

Although athletes suffering a type I strain often initially present with greater functional deficits compared to type II strains, their recovery time has been reported to be quicker (4). The study by Askling et al. (4) demonstrated that athletes who suffered from both type I and II strains could perform strength and flexibility assessments at > 90% of the uninjured leg six weeks post injury. However, their self-reported time to return to pre-injury levels of performance were markedly different (type I: average of 16 weeks (range = 6-50 weeks); type II: average of 50 weeks (range = 30-76 weeks)), identifying the need for both subjective and objective information during the rehabilitation period (4). It should be noted that in the work of Askling et al. (4) these two different types of HSI were present in two different sports populations (type I; sprinters and type II; dancers), which may have influenced the difference in recovery times.

HSI Incidence, Time-Loss, Time of Injury Incidence and Typical Severity

The incidence and time-loss of HSI across several sports is summarised in Table 1. Within professional soccer, HSI incidence has been widely reported. Petersen et al. (79) reported an average of 3.4 (range = 1-5) HSI per club per season, Woods et al. (114) reported a higher average of 5.0 (range = 0-16) per club, and Ekstrand et al. (29) claimed that clubs could expect around 7 hamstring strain injuries per season. This is similar to those reported for Australian football, where Orchard et al. (76) reported 6 injuries during the 1995 season. Hamstring strain injury incidence also highlighted in the more recent 2018 Australian Football League (AFL) injury report, with 6.35 new HSI injuries per club per season (1). The similar number of HSI per club per season reported within these two studies provides some evidence that HSI occurrence within AFL has remained consistent across 23 seasons (1,76). Furthermore, the AFL injury report also demonstrated a HSI re-injury rate of 20%, defined as the same injury type, on the same side in the same season (1). Injury incidence rates have also been reported for rugby union (5.6 per 1000 player hours) (16), cricket (22.5 per 1000 team days) (77) and a range of NCAA sports (3.05 per 10,000 athlete exposures) (26). Finally, within a cohort of student dancers, a retrospective analysis found that 51% of athletes reported suffering posterior thigh pain at some point in their careers (3). Thus, the prevalence of HSI appears common across a multitude of sporting populations.

Time-loss due to hamstring injury can be seen as a more important factor than injury incidence, as ultimately the amount of time-missed by an athlete may have a direct effect on team performance and results (41). This is highlighted in the 2018 AFL injury report, which noted that during a 22 game season, clubs could expect to lose 25.19 matches to HSI, which may ultimately have a detrimental effect upon team selection (1). The reporting of time-loss in professional soccer appears to be fairly consistent across the literature, with Woods et al. (114) (18 days), Ekstrand et al. (31) (17 days) and Petersen et al. (79) (21.5 days) all reporting similar average time-loss values per injury. Woods et al. (114) further report that during this 18 day time-loss period, athletes are likely to miss 3 competitive soccer matches. Within NCAA athletes 37.7% of hamstring strain injuries incurred a time-loss of < 24 hours, with 6.3% reported to miss > 3 weeks (26). The severity of hamstring injuries was further displayed by Ekstrand et al. (29) who stated that 12% of injuries classed as severe (time-loss > 28 days) were seen to be hamstring injuries.

HSI incidence (31,79,114) and rate (26) is reported to be more prevalent during competition than in training. This may indicate the increased intensity of match-play, but also suggests that training may not sufficiently prepare athletes for the demands of competition (29). This notion is further supported by Ekstrand et al. (29) who states that hamstring strains are more prevalent in-season compared to pre-season, highlighting the importance of continually training the hamstring group all year round within athlete development programmes. Furthermore, it has been reported that 47% of hamstring strains in professional soccer occur in the final third of the first and second halves, suggesting that fatigue may be a contributing factor (114).

A magnetic resonance imaging (MRI) study of hamstring injuries within professional soccer highlighted 207 injuries, of which 13% were classified as grade zero (negative MRI with no visible pathology), 57% grade one, 27% grade two and 3% grade three (30). Similar findings could be seen within a second study in professional soccer that reported 1614 hamstring injuries, with 10% reported as minimal, 21% mild, 54% moderate and 15% severe in nature (31). The findings within these studies would suggest that the majority of hamstring injuries within soccer athletes are minimal to moderate in nature and/or classified as grades zero to two.

Mechanisms of Injury

Amongst the literature presented in Table 1, running and sprinting was shown to be the primary mechanism for hamstring injury (16,26,30,36,114). Ekstrand et al. (30) highlight that sprinting and high speed running was responsible for 70% of hamstring injuries amongst soccer players. Similarly, Gabbe et al. (36) found that 73% of hamstring injuries amongst elite Australian footballers (AF) could be attributed to running or sprinting. These figures are much higher than those reported by Woods et al. (114) who claimed running was responsible for 57% of hamstring injuries. The percentage of HSI attributed to running and sprinting have also been reported for other team sports including: American football (48.4%), lacrosse (men 35.6%; women 48.5%), basketball (men 25%; women 35.1%) and individual sports such as outdoor track and field (men 58.3%; women 46.9%) in a study of NCAA athletes (26). Furthermore, within rugby union athletes, the “backs” playing position have been shown to suffer a greater incidence of hamstring injury, possibly owing to the greater demand of high-speed running upon this playing group (16).

Other hamstring injury mechanism’s reported within the literature include: stretching (6,30,114), sliding (30), turning (30,114), twisting (30,114), kicking (6,30,114), overuse (26,30), jumping (30,114) and during escape/sparring/take-down manoeuvres in sports like wrestling (26). Collectively, although these actions are not as common as sprint related injuries for team sport athletes; however, their importance should not be understated. The action of kicking, either a ball or an opponent, has also been highlighted within the literature as an HSI mechanism (6,15,37). Previously, Askling et al. (6) has identified HSI during high kicking actions in ballet, taekwondo and soccer. Within rugby union athletes Brooks et al. (15) explained that kicking was responsible for approximately 10% of HSI and that these were seen as the most severe in terms of time lost (36 days lost). Furthermore, Gabbe et al. (37) reported that in community level Australian football, 19.2% of HSI were attributed to kicking the ball. Additionally, within professional soccer, up to 55% of HSI have been reported in the preferred kicking leg (30). Furthermore, Lord et al. (59) reported that 100% (n = 20) of the injured subjects within their study suffered the HSI within the preferred kicking leg. Although the reason for this has not been well established, Rahnama et al. (83) found the knee flexors of the preferred kicking leg to be significantly weaker ($p < 0.05$) than the non-kicking leg when measured at 2.09 rad/s and that 68% of athletes tested had between-limb differences in strength > 10%. Therefore, as strength deficits have been highlighted as a risk factor for HSI, it is reasonable to assume that the reduction in strength of the preferred kicking leg plays a role in its increased susceptibility to injury, especially when this is coupled with the possibility that this limb is overloaded during performance (83).

Stretching and performing side and sagittal splits have been reported as a mechanism of injury in a variety of sports including: ballet, dance, rock climbing, tennis, soccer, judo, ice hockey, and gymnastics (6). This type of injury is commonly reported within dancers. In-fact, Askling et al. (3) stated that within a cohort of student dancers, 88% of acute HSI injuries were suffered during slow activities such as performing splits. In other sports, such as professional soccer, stretching and sliding related HSI have been reported with less regularity, with Ekstrand et al. (30) stating that they account for 5% of all HSI. Finally, 13 HSI were reported in a population of NCAA wrestling athletes, with actions such as sparring, takedown manoeuvres and performing escapes all reported to be responsible for 15.4% (each) of all HSI (26). Although running and sprinting are reported as the most common causes for HSI, identifying other possible mechanisms is important information that can enable practitioners to understand the risk of HSI and develop appropriate injury prevention plans for their given sport.

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Table 1. Hamstring injury incidence and time lost across a number of sports.

Injury Risk Factors

Several risk factors relating to hamstring injury and re-injury have been reported within the literature. These can be categorized into two distinct groups: modifiable and non-modifiable. Risk factors classified as modifiable are often seen as factors where the risk can be reduced through a targeted training intervention (e.g., increasing an athlete's strength). Non-modifiable risk factors are those which are out of the control of the athlete and practitioner (e.g., age of the athlete). Oftentimes, these risk factors can be specific for each sport. For example, high-speed running loads are likely a risk factor in soccer as opposed to wrestling, whereas some may be global to all athletes, such as poor levels of strength. These risk factors and their implications for training are discussed in the following section.

Modifiable Risk Factors

Fatigue

As previously mentioned, hamstring injuries often occur towards the end of match-play, presumably with fatigue being a contributing factor. Several authors have investigated the role fatigue may have upon other established risk factors, such as eccentric knee flexor strength, and therefore the ability of the hamstrings to generate and tolerate force. Small et al. (95) and Greig (39) both used a soccer-specific fatiguing protocol to measure the impact of fatigue upon measures of torque obtained via isokinetic dynamometry at contraction speeds of 60, 120, 180 and 300°/s respectively. It was found in the work by Small et al. (95) that eccentric peak hamstring torque and the functional hamstring:quadricep (H:Q) ratio (eccentric hamstrings vs. concentric quadriceps) was significantly reduced during the fatigue inducing protocol (95). Furthermore, the authors found no significant changes in concentric peak torque of both the hamstrings and quadriceps (95). Greig (39) also found no significant changes in concentric knee flexor and extensor peak torque at all contraction speeds tested, but were able to demonstrate significant reductions in peak eccentric hamstring torque which were more evident at the faster contraction speeds. This indicates that the hamstrings are more greatly affected when having to produce force quickly when fatigued, which may be particularly relevant when considering the relationship between high-speed running and HSI (39).

The reduced ability of the hamstrings to produce force when under fatigue is also supported by Lord et al. (58,59). Their first study highlighted significantly reduced mean horizontal force production in limbs previously suffering a HSI during a 10 x 6s repeated sprint test on a non-motorized treadmill (58). The second study measured peak concentric knee flexor and extensor torque during isokinetic testing measured at 180°/s, following the completion of the same 10 x 6s repeated sprint protocol (59). They found significant reductions in isokinetic knee flexor torque and the concentric H:Q ratio only in limbs that had previously suffered a hamstring injury (59). Furthermore, the decline in knee flexor torque was also able to correctly identify the previously injured limb with 100% accuracy (59). Therefore, it appears that fatigue may also play a prominent role in hamstring re-injury rates as the previously injured limb appears to suffer greater loss of function when in a fatigued state (58,59). Coratella et al. (23) also found significant increases in peak joint torque angle, both during concentric and eccentric contractions, following a fatigue inducing protocol which consisted of the Loughborough Intermittent Shuttle Test (a 20-metre shuttle run that involves sprinting, walking and running at 55% and 95% of an individual's maximal aerobic speed). The authors hypothesized that these fatigue induced changes (where the hamstring exerts greater force at shorter muscle lengths), may highlight their impaired ability to act against the quadriceps during near maximal knee extension when the hamstring is in a lengthened position (23). However, it should be noted that these measurements were made in a seated position, and therefore are not indicative of sprint running gait (23).

The reduced ability of the hamstrings to produce force at longer muscle lengths, and maybe more importantly absorb opposing force, may help to enhance the understanding of fatigue as a risk factor for injury. During sprint running, the hamstrings work both eccentrically to decelerate knee extension to counteract inertia of the leg swing during the terminal swing phase, and concentrically as an active hip extensor (57,78). It is at this time (terminal swing), that the biceps femoris, semitendinosus and semimembranosus are subjected to peak strain, force and energy absorption (86). The reduced ability of the hamstrings to both absorb energy and produce force once fatigued is likely to impair their ability to perform subsequent tasks, and when accompanied by increased quadriceps dominance (as indicated by the reduced H:Q ratio), this may predispose the hamstrings to heightened injury risk (21,23,57,86,95). Furthermore, altered hamstring muscle activation patterns (once fatigued), have been proposed as a possible cause of injury (80,110). Pinniger et al. (80) explain that under fatigue there is a significant increase in the duration of hamstring EMG activity due to the earlier onset of muscle activation. It has been suggested that this may be a mechanism to overcome the reduced force generation capabilities of the hamstring muscle group (80,110).

Biceps Femoris Fascicle Length

The contribution of the biceps femoris fascicle length in HSI occurrence and re-occurrence has been discussed within the literature (9,34,101,102). The prospective research by Timmins et al. (102) in elite soccer players reported that short biceps femoris fascicle lengths of < 10.56 cm increased the risk of HSI by 4.1 fold. Furthermore, a retrospective study by Timmins et al. (101) found that post injury both fascicle length and fascicle length relative to muscle thickness was significantly ($p < 0.001$) reduced compared to the uninjured contralateral limb.

It has been hypothesised that the contributing mechanism to the increased risk of injury to shorter fascicles may be owed to a reduced number of in-series sarcomeres, which may be excessively lengthened during eccentric contractions (9,102). This may be exacerbated further following injury with the presence and formation of scar tissue, which may increase the burden placed upon the fascicles during excessive lengthening (34,52,93). Therefore, it can be seen that short biceps femoris fascicle lengths may play a role in both first time HSI and injury reoccurrence and should be a factor which is considered in both injury prevention and rehabilitation programmes.

High-Speed Running Loads

Running at high-speed or sprinting have already been identified as a mechanism for hamstring injury. It has been previously well reported that spikes in athlete load increase the risk for soft tissue injury, and that appropriately planned vigorous training may decrease the risk of injury (38,48). Malone et al. (63) studied exposure to high velocity running events in 37 elite Gaelic football athletes and found that both under and over exposure to these events increased the risk of injury. Specifically, those performing 6-10 maximal velocity efforts per week were at reduced risk of injury compared to those completing < 5 efforts, and those completing > 10 bouts at a significantly higher risk of injury (63). They further explained that those athletes who were exposed to events over 95% of their maximal velocity benefitted from a protective effect of training (63). A secondary study by Malone et al. (61) reported that large weekly changes of 351-455 m in high-speed running (> 14.4km/h) and 75-105 m of sprint speed (> 19.8km/h) increased the risk of injury. Furthermore, athletes who completed a moderate distance (high-speed: 701-750 m; sprint speed: 201-350 m) were at reduced risk compared to those who completed relatively low amounts (high-speed: < 674 m; sprint speed: < 165 m) (61).

This is somewhat supported by Duhig et al. (28) who reported that athletes completing higher than typical mean (calculated from each athlete’s 2-yearly session average) high-speed running (> 24km/h) distances in the four weeks prior to injury, were at greater likelihood of suffering a hamstring injury. Furthermore, the study by Ruddy et al. (85) involving 220 elite Australian footballers supports the monitoring of running distances completed above

24km/h in relation to HSI. They reported that absolute weekly distance covered above 24km/h (> 653 m, relative risk (RR) = 3.4), absolute week to week change in distance covered above 24km/h (> 218 m, RR = 3.3), relative week to week change in distance covered > 24km/h (> 2.00, RR = 3.6) and distance covered above 24km/h expressed as a percentage of that covered above 10km/h (> 2.5%, RR = 6.3) provided the largest significant risk factors of suffering a HSI in the subsequent week (85). However, despite the significant relative risk values, the authors report a substantial overlap in running distances between those subsequently injured and those uninjured (85). Therefore, although providing an association between distances covered above 24km/h and HSI, it was not possible to predict HSI at the individual athlete level, which is further highlighted by none of the absolute running variables reporting both sensitivity and specificity values above 0.6 (85). Although not all of the aforementioned studies are specific to hamstring injury, it appears that inappropriate high-speed and sprint running loads may lead to an increase in soft tissue injury. Therefore, as high-speed running and sprinting have been reported mechanisms for hamstring injury, exposure to these type of events warrants particular attention as a risk factor for HSI.

Strength and Intra-limb and Inter-limb Asymmetry

Hamstring strength and asymmetry have been widely proposed as modifiable risk factors (12,19,25,75,76,100,102,116). Asymmetry may present in two forms: inter-limb (the difference between two limbs) (12,25) and intra-limb (the difference between the quadriceps and the hamstrings within the same limb) (116). Intra-limb differences are often reported as a ratio (116), whereas inter-limb differences are typically displayed as a percentage (12,25). Oftentimes, the concentric H:Q has been investigated to highlight strength discrepancies between the hamstrings and quadriceps. The literature highlights that a significant reduction in the H:Q ratio was evident in subsequently injured limbs in comparison to uninjured athletes and/or the uninjured limb (19,76,116). In-fact, Yeung et al. (116) explain that when measuring concentric strength at an angular velocity of 180°/s, a ratio lower than 0.6 led to a 17 times increased risk of injury. However, in a study of 614 elite soccer players across 4 competitive seasons, the H:Q was not supported as a potential risk factor for future HSI, with the authors reporting no relationship between H:Q measurements and subsequent HSI (109). No significant differences were noted between the injured and uninjured limbs (n = 167) in the concentric H:Q measured at 60 and 300°/s (109). Furthermore, following multiple logistic regression analysis, odds ratios were also reported to be non-significant (n = 563) at both 60 and 300°/s (109). Thus, given the sample size and time course of the study, the value of the H:Q in relation to HSI prediction could be questioned.

Due to the previously mentioned primary role of the hamstring muscles (to function eccentrically to decelerate knee extension during the late swing phase), it may be argued that a more functional assessment of the H:Q ratio would be to assess the eccentric action of the hamstrings vs. the concentric action of the quadriceps (23,24). This method was retrospectively employed by Croisier et al. (24) who discovered significant imbalances in the functional ratio between the injured (0.73 ± 0.24) and uninjured limb (0.90 ± 0.16; $p < 0.01$) within subjects with previous hamstring injury. However, a prospective study by Bennell et al. (11) found no predictive benefit of isokinetic testing, including the comparison of functional H:Q ratio. Similarly, Van Dyk et al. (109) found no significant differences between injured and uninjured limbs when studying the functional H:Q ratio. However, it should be noted that eccentric hamstrings torque was measured at 60°/s and concentric quadriceps torque at 300°/s.

Furthermore, the hamstrings were not tested eccentrically at faster contraction speeds (like the quadriceps) which may be more indicative of high-speed running (109). As previously mentioned, Small et al. (95) found significant reductions in the functional H:Q ratio during a multidirectional soccer-specific fatigue inducing protocol, which may suggest that performing these ratio's within a fatigued state may be more sensitive to injury prediction. However, it should be noted that Small et al. (95) did not report upon any relationships with injury and therefore further prospective research within this area is warranted.

It has been reported across several studies that hamstring injury often occurs within the weaker limb, indicating that between-limb strength differences may be a factor for consideration with HSI (25,76,100). The work of Sugiura et al. (100) explains that significant inter-limb asymmetries existed between injured and non-injured limbs in isokinetic testing of both the eccentric hamstrings and concentric hip extensors (which include but are not limited to the hamstrings). Furthermore, Orchard et al. (76) found that a significantly increased risk of injury was present if an individual displayed a hamstring to opposite hamstring ratio of < 0.92. Despite this being a useful finding, this value reported as a percentage difference between limbs may be of more practical use and better understood by practitioners in the field. This is further supported by the study of Croisier et al. (25) involving 462 soccer players. They found that those with significant imbalances ($> 15\%$ bilateral difference in concentric or eccentric hamstring strength) had a 4-5 times increased risk of injury (25). The authors reported that reducing these imbalances to $< 5\%$ significantly reduced the risk of injury from a relative risk ratio of 4.66 to 1.43 (25).

Strength imbalances were further highlighted as a risk factor when tested during the Nordic hamstring exercise (12). In a prospective study, it was found that the subsequently injured limb was significantly weaker than the uninjured contralateral limb and that differences of $\geq 15\%$ and $\geq 20\%$ increased the risk by 2.4 and 3.4 fold respectively (12). Further measurements made during the performance of the Nordic hamstring exercise provide additional support for strength as a risk factor. Both Opar et al. (75) and Timmins et al. (102) report that weaker limbs and athletes were at an increased risk of injury. In a population of 210 elite Australian footballers eccentric strength below 256 Newtons (N) at the start of pre-season and 279 N at the end of pre-season were said to increase risk by 2.7 and 4.3 fold respectively (75). This is further corroborated by Timmins et al. (102) who found that for every 10 N increase in eccentric knee flexor strength the risk of injury fell by 8.9%. Finally, a reduction in hamstring strength, in comparison to uninjured limbs/subjects, following a hamstring injury has been widely reported amongst the literature (50,54,73,74). Although this does not add any prospective predictive value per se, as it is unknown if the reduction in strength can be attributed to previous injury or if the weakness is the result of previous injury; thus, testing previously injured athletes may provide some value. As strength deficits and previous injury have been identified as risk factors, coupled with the role that the normalization of strength imbalances can play on reducing risk (25), identifying those individuals still at risk following previous injury may help in the planning of targeted training interventions.

Insufficient/Inadequate Warm-Up

Oftentimes, an appropriately planned warm-up which adequately prepares an athlete for training and match-play has been recommended in order to reduce injuries (32,70,97,99), although there is a lack of empirical evidence to support this theory for HSI. A systematic review by Fradkin et al. (32) found insufficient evidence to both promote or discourage pre-exercise warm-up for the reduction of injury occurrence. Of the five studies included within the review, three found that the inclusion of the warm up significantly reduced injury, whereas two found no significant effect upon injury occurrence (32). The authors conclude that although there is insufficient evidence to support or discourage the implementation of a warm up to prevent injuries, the weight of evidence is in favour of implementing a warm up strategy (32).

Recently, structured warm-up protocols, such as the FIFA 11+ (also referred to as the F-MARC 11+), have been implemented with the aim of reducing lower limb injury occurrence (40,94,97). Soligard et al. (97) reported that although statistical significance had not been reached, a reduction in overall lower limb injury could be seen due to the implementation of the structured warm-up intervention. When looking at the hamstring specifically, the intervention group (n = 1055) suffered 5 injuries, with the control group (n = 837) suffering 8 injuries (97). However, the incidence per 1000 playing hours was 0.1 in the intervention group and 0.2 in the control group, which was not significantly different (97). It should be noted that hamstring injury rates pre-intervention were not reported, which would have allowed for better comparisons to be made as to the effectiveness of the intervention.

The reports by Silvers-Granelli et al. (94) and Grooms et al. (40) both support the value of the FIFA 11+ programme within athletic training after discovering significant reductions in hamstring injuries compared to a control group and a reference group respectively across one entire season. It was reported that 55 and 16 HSI were experienced by the control and intervention group respectively, resulting in the intervention reducing the likelihood of injury 2.74-fold ($p < 0.001$) (94). However, a better understanding of the intervention's success could have been gained if these HSI occurrences had been compared to those experienced during the pre-intervention period. In the study by Grooms et al. (40) the intervention group, who performed the FIFA 11+ programme 5-6 times per week, reported only one hamstring injury compared to the five reported by the control group. However, it should be noted that the FIFA 11+ programme includes the Nordic curl exercise, which has been widely reported to reduce hamstring injuries (2,90,107). Therefore, it could be suggested that increases in strength, derived through the inclusion of the Nordic curl, are the largest factor in reducing HSI injuries within the FIFA 11+ programme, and not the overall process of performing a warm-up. Although the potential benefit of the warm-up is not fully supported by the research provided here, there is some evidence to suggest that an appropriately planned warm-up may aid the reduction of injuries.

Oftentimes, flexibility/ dynamic stretching exercises are included as part of a warm-up routine (49). However, the evidence to suggest that altered levels of flexibility are a risk factor for hamstring injury are inconsistent across the literature. Bennell et al. (10) studied 67 Australian football players and concluded that there were no significant differences in hamstring flexibility between those who subsequently sustained an injury and those who remained uninjured. Similarly, Orchard et al. (76) found no correlation between injury and hamstring flexibility as measured via the sit and reach test in a population of Australian footballers. However, it should be noted that the sit and reach test is not specific to hamstring flexibility, and often results can be impaired by an athletes hip mobility and their ability to flex the spine (76). It is also worth noting that the test is unable to differentiate between limbs, potentially masking any imbalances that may be present (76). These findings are further supported by both Hennessy and Watson (43) and Yeung et al. (116) who also found no correlation between hamstring flexibility and injury.

In contrast, Witvrouw et al. (112), prospectively studied the relationship between hamstring flexibility and hamstring injury among 146 professional soccer players. They reported that, in comparison to their uninjured counterparts, those injured displayed significantly reduced levels of flexibility (< 90° during passive straight leg raise; $p = 0.02$) (112). The differences in the results presented here may be partly attributed to the different methods employed to ascertain hamstring flexibility. However, both Witvrouw et al. (112) and Yeung et al. (116) measured flexibility through a passive straight leg raise and reported opposing results. With such discrepancies existing within the literature the role of flexibility in hamstring injury should be viewed with caution, especially when a multitude of factors may contribute to hamstring injury.

It should be noted that in a retrospective study performed by Jonhagen et al. (50) previously injured sprinters showed significantly reduced hamstring flexibility during a passive hamstring raise compared to a group of uninjured sprinters (average RoM = 67.2° vs 74.1°; $p < 0.05$). The reduction in flexibility post hamstring injury is further supported by Maniar et al. (64) whose meta-analysis showed reduced hamstring flexibility up to 40 days post injury. Therefore, it may be more important to consider flexibility as a risk factor in those previously suffering from a HSI in order to reduce the risk of a subsequent injury.

Lumbo-Pelvic Hip Control

Despite only a relatively small amount of current evidence, lumbo-pelvic hip control should be considered as a risk factor for HSI. An increased anterior pelvic tilt during sprint running is believed to place the hamstrings into an elongated position, therefore increasing the strain placed upon them (47,96). This may be particularly critical during the terminal swing phase, when the biceps femoris long head is placed under increased stretch, which may be further exacerbated by the presence of an anteriorly tilted pelvis (21,47,96). This may result in an increased chance of suffering a HSI, however, further research is required within this area.

Furthermore, restricted sagittal plane motion at the hip, as measured via the modified Thomas Test, has been shown to reduce gluteal activation (67). This may be important to HSI risk, as the work by Schuermans et al. (89) highlights proximal neuromuscular control as a risk factor for HSI. They studied muscle activation, via surface EMG, during sprint running in a population of 60 amateur soccer players (89). During the 1.5 season follow up period, they reported that those athletes not suffering a HSI had significantly ($p = 0.027$) greater gluteal muscle activity during the front swing phase and increase trunk activity ($p = 0.042$) during the back swing (89). Therefore, it may be hypothesised that restricted motion at the hip has the potential to inhibit gluteal activation, and subsequently proximal neuromuscular control, which could lead to an increased risk of suffering a HSI (67,89).

Non-Modifiable Risk Factors

Previous Injury

A previous HSI has often been identified as a risk factor for future HSI (12,26,31,36,77,79,102,114). Re-injury rates have typically been reported at 12-13% (26,31,114), with Petersen et al. (79) reporting greater values of 25%. However, it is important to note the significantly different methodological approaches in the work of

Petersen et al. (79), who define a HSI as any self-reported posterior thigh pain, irrespective of time loss, which may account for the reported increased re-injury rate. Gabbe et al. (36) found that amongst Australian footballers, a HSI sustained within the previous 12 months, to be the strongest independent predictor of future injury (odds ratio = 4.3; $p = 0.003$). It has also been reported amongst international cricketers that following a HSI, an athlete is at 3.7 times higher risk of suffering a further injury within the same season, and at 2.7 times higher risk in subsequent seasons (77). This risk factor is slightly lower than those reported for both rugby union athletes (4.1 times higher) (12) and Australian footballers (4.9 times higher) (110). Previous knee ($p = 0.039$) and groin ($p = 0.015$) injuries were also reported as significant risk factors for future HSI (110).

Although previous injury is seen as a non-modifiable risk factor it has been highlighted that those with previous injury had reduced eccentric hamstring strength (102) and inter-limb asymmetries (12) when performing the Nordic hamstring exercise. Furthermore, short biceps femoris fascicle length was also reported as a contributor to multiple hamstring injuries (102). Therefore, it could be speculated that improving these physical attributes may aid in the prevention of repeat HSI (12,102).

Age

A study by Gabbe et al. (35) identified that athletes ≥ 25 years of age had a higher hamstring injury incidence (19.2%) than those ≤ 20 years of age (6.9%). A separate study by Gabbe et al. (37) found that athletes ≥ 23 years old were at a greater risk of hamstring injury. It has also been reported that for every one year increase in age the risk of hamstring injury increases by 1.3 fold when assessed independently of previous injury (110). It was also reported amongst a large cohort of track and field athletes that masters athletes (> 40 years of age) were significantly more likely to suffer a HSI than high school and collegiate athletes (72). It has been hypothesised that the role of age in increased injury risk may be attributed to increased body weight, decreased hip flexor flexibility (35), reduced eccentric hamstring strength and short biceps femoris fascicle length (102). Therefore, maintaining optimal body composition, flexibility of the hamstring and hip musculature and eccentric hamstring strength may be beneficial to hamstring injury prevention amongst older athletes.

Practical Applications: Injury Prevention Programme

As the literature highlights several contributing factors to HSI and reinjury rates, injury prevention programmes should be multifaceted in nature and address all of the potential modifiable risk factors. The programme outlined (Figure 1) is aimed at team sport athletes, who are at greatest risk of suffering a type I strain (sprint related). The programme is divided into four stages, with stages 1-3 representing a pre-season period, and stage 4 an in-season phase which may be implemented for maintaining performance levels. The programme outlined in figure 2, is aimed at athletes who are at greater risk of suffering a type II strain (such as dancers and combat athletes), and is divided into three progressive stages which can be implemented in the lead up to a competition. It is intended that both injury prevention programmes should not stand alone, and instead should be integrated into the wider athlete performance plan.

Warm-Up

Although there is not overwhelming evidence to suggest that a structured warm-up is beneficial to the reduction of HSI, warm-ups are common place in sports performance in order to prepare the athlete both mentally and physically for activity (49). During this preparation phase, team sport athletes should be gradually exposed to maximal velocity efforts (i.e., 40 m sprints at 65, 75, 85, 95 and 100% of perceived maximal velocity), as well as gradually increasing kicking (for appropriate sports) distances (i.e., 10, 20, 30, 40 m kicks), particularly as these events have been highlighted as injury mechanisms within these populations (6,15,16,26,30,36,37,114). Similarly, in sports where type II HSI is more likely, performing sport specific movements (i.e., high kicks, sagittal and side splits) at gradually increasing intensity and range can be incorporated into the preparation phase of the warm-up.

The warm up also affords practitioners with a time period in which to deliver training protocols, which cannot only aid athletic movement competencies (49), but also injury prevention (40,94,97). The FIFA 11+ recommends the integration of the Nordic curl as part of a structured warm-up to prevent HSI (40,94,97). Furthermore, other exercises, including those that may play a role in increases in flexibility, may also be included within a structured warm-up in order to improve the overall time efficiency of the athlete performance programme.

Although there is limited evidence to suggest that reduced levels of flexibility play a significant role in increasing the risk of HSI (10,43,76,112,116), it has been demonstrated that flexibility training can have a positive effect on biceps femoris fascicle lengths (33). The study by Freitas et al. (33) described the effects of an 8-week high-volume stretching intervention, which involved stretching the hamstring at maximum range of motion for 450 seconds 5 times per week, on biceps femoris muscle architecture, as measured via ultrasound sonography. They reported significant increases (+ 12.3mm, $p = 0.04$) in biceps femoris fascicle lengths as well as significant improvements in passive knee extension range of motion (+14.2°, $p = 0.04$) (33). As short biceps femoris fascicle lengths have been highlighted as a potential risk factor for HSI (102), it would appear prudent to include elements of flexibility training within a HSI prevention programme. In order to increase time efficiency, such exercises can be incorporated into a structured warm-up routine.

Eccentric Strength

Strength, and more specifically eccentric strength, has been previously highlighted as a contributing risk factor for HSI, demonstrating the need for the inclusion of eccentric strength exercises within HSI prevention programmes. When selecting strength-based exercises it is important to note which type of HSI the athlete is likely to suffer, and therefore which muscle group is likely to be the site of damage (type I; biceps femoris, type II; semimembranosus) (5,6,14). This enables practitioners to programme exercises with a focus towards a particular hamstring muscle (14). The work by Bourne et al. (14) provides a framework for selecting the most appropriate strength training exercises within HSI prevention programmes.

Team sport athletes (figure 1), are most likely to suffer a type I HSI (sprint related strain), but may also experience type II strains in actions such as kicking (5,6). Within these populations the inclusion of the Nordic curl exercise in injury prevention programmes has been well reported within the literature (2,90,107). Arnason et al. (2) implemented a flexibility and hamstring strength training intervention amongst elite soccer players from Iceland

and Norway. They found no effect upon injury reduction amongst those players performing flexibility training alone ($p = 0.22$) (2). However, when Nordic hamstring curls were included as part of the programme hamstring injury was reduced by 65% compared to the control group (2). These findings are further corroborated by Van der Horst et al. (107), who found that the inclusion of Nordic hamstring curls within a 13-week training programme significantly reduced the incidence of hamstring injuries compared to a control group (intervention group = 0.25 per 1000 player hours; control group = 0.8 per 1000 player hours; $p = 0.005$) within a large population of amateur soccer players. Furthermore, in the year prior to the intervention, 24 and 20 HSI injuries were reported in the intervention and control group respectively (107). This was reduced to 11 in the intervention group but increased to 25 in the control group during the 52-week surveillance period (which included 13 weeks of the intervention) (107). A successful Nordic hamstring intervention was also seen within a group of baseball athletes implemented across the entire 2012 season (90). It was demonstrated that zero hamstring injuries were reported amongst the intervention group, compared to the ten suffered by the control and non-compliant group (performing < 3.5 Nordic curls per week) (90). Furthermore, upon the implementation of the Nordic curl intervention, the time loss owing to HSI was reduced to 136 days, compared to 273 and 309 days in previous seasons (90).

The success of the Nordic curl exercises within these studies may be attributed to its positive affect upon biceps femoris long head muscle volume, size and strength. Seymore et al. (92) studied the effect of the Nordic curl exercise combined with stretching compared to a control group who only performed stretching exercises. The intervention consisted of a 6-week Nordic curl programme where frequency (1-3) and volume (2 x 5 reps, increasing to 3 x 8-12 reps) were progressively increased (92). The group that performed Nordic hamstring exercises in addition to stretching saw significant increases ($p < 0.05$) in biceps femoris long head physiological cross-sectional area (16.08 ± 6.43 cm^2 vs. 18.05 ± 7.33 cm^2) and muscle volume (131.46 ± 43.32 cm^3 vs. 145.2 ± 46.42 cm^3) compared to baseline (92). Furthermore, Bourne et al. (13) found that Nordic curl training promoted longer biceps femoris long head fascicle lengths and greater biceps femoris long head, short head and semitendinosus muscle volume when training sessions were performed twice a week for ten weeks. However, it should be noted that within the same study, the hip extension exercise promoted greater changes in biceps femoris long head and semimembranosus (where the Nordic curl promoted no significant differences to the control group) muscle volume (13).

Figure 2 highlights a HSI prevention programme aimed at reducing the incidence and severity of type II strains. Within this population of athletes, the site of injury is most commonly the semimembranosus, and therefore exercises should be selected accordingly (6,14). This should include the "Romanian" or "stiff-leg" deadlift, which has been reported to show significantly ($p < 0.01$) higher levels of semimembranosus activation than both the biceps femoris and semitendinosus (71). The research by Ono et al. (71) further explained that following the performance of stiff-leg deadlifts, a significant increase in both magnetic resonance imaging transverse relaxation time (T2) value and cross sectional area of the semimembranosus were observed.

Strength Imbalances

Additional to the development of eccentric hamstring strength, there is also a need to address both intra (differences between the quadriceps and the hamstrings in the same leg) and inter (differences between hamstrings bilaterally) limb strength imbalances within HSI prevention programmes. Previous research by Ruas et al. (84) has demonstrated that eccentric strength training significantly ($p \leq 0.05$) increased the functional H:Q ratio following a 6-week intervention (H:Q pre; 0.73 ± 0.092 vs H:Q post; 0.87 ± 0.098). Furthermore, Holcomb et al. (46) reported that a 6-week hamstring emphasised strength programme was able to significantly ($p < 0.05$) increase the functional H:Q ratio from 0.96 ± 0.09 to 1.08 ± 0.11. The inclusion of the Nordic hamstring curl in strength programmes aimed at optimizing the functional H:Q ratio is somewhat supported by Delextrat et al. (27). They reported that significant ($p < 0.05$) increases of 27.8% in the functional H:Q ratio were seen following a 6-week training programme (27). However, it should also be noted that in comparison, the eccentric leg curl promoted greater improvements (38.3%) than the Nordic hamstring curl, and that for both exercises these results were only evident within the non-dominant limb (27). This may suggest that additional unilateral strength training exercises should be included within HSI prevention programmes aiming to address intra-limb strength imbalances.

Alongside the primary "lifts" (Nordic curl and stiff-leg deadlift), supplementary unilateral exercises have been included within both programmes, outlined in figures 1 and 2, including: single leg stiff-leg deadlift, single leg slider curl and both the Askling diver and glider exercises. The aim of these exercises is to both correct muscular imbalances (intra and inter limb) and to promote joint stability. Previous research has suggested that inter-limb strength imbalances should be reduced to <5% in order to significantly reduce the risk of HSI (25). In order to achieve this, the single leg stiff-leg deadlift is included within figure 1 and has been previously recommended within hamstring training programmes (60,66), despite Tsaklis et al. (103) stating that hamstring EMG was relatively low for this exercise. However, it should be noted that this exercise was performed without external load (i.e., body weight only) during this study, which may have influenced the results (103). The single leg slider curl has also been investigated by Tsaklis et al. (103) who measured EMG outputs of ten hamstring based exercises and found the slider curl to have the highest mean EMG activation of the biceps femoris and semitendinosus muscles. However, their results should be viewed with caution as the twenty participants performed all exercises in the same order, albeit with a 5 minute rest period between each, with no randomization (103). Furthermore, their study did not differentiate between contraction types (concentric and eccentric) and only provided results for combined contraction outputs, both of these methodological factors may have affected the results of the study (103).

The Askling diver and glider form part of the Askling L-protocol (lengthening exercises) which has been shown to be successful within hamstring rehabilitation programmes (7). During the study, the L-protocol reported significantly shorter (mean 28 days, range 8-58 days) return to play time, compared with a conventional hamstring training programme (mean 51 days, range 12-94 days) (7). EMG studies of these two exercises have shown the hamstrings to be eccentrically contracted at similar working points to that of the swing phase during high-speed running (91), further supporting their use within prevention and rehabilitation programmes.

The strength training component should be included as part of the wider strength training programme (i.e., athletes should also be performing other exercises to develop all round athletic performance). It may be prudent for practitioners to also consider the rear foot elevated split squat (RFESS) within the overall athletic development plan. The work by McCurdy et al. (65), who compared EMG measurements of the RFESS and the traditional back squat exercise, at 85% of a subjects three repetition maximum for each exercise, support its inclusion within athletic training programmes that have an emphasis on HSI prevention. Their research showed that the RFESS recorded significantly ($p < 0.01$) greater mean and mean peak hamstring activation, whereas the traditional back squat showed significantly greater recruitment of the mean quadriceps ($p < 0.05$), mean peak quadriceps and mean Q:H ($p < 0.01$) (65). As the RFESS appears to provide a greater demand on the hamstrings, compared to the back squat (which places a greater emphasis on the quadriceps), it may be seen as a viable alternative to the traditional back squat exercise in athletic programmes when an emphasis on hamstring conditioning is required (65).

Fatigue and Fitness

Fatigue has been previously linked to HSI occurrence due to injuries being reported to occur towards the end of games, possibly owing to the effect of fatigue on the reduction of eccentric knee flexor strength. Furthermore, it has been previously demonstrated that those with reduced aerobic fitness (as measured via a 1 km time trial) were at an increased chance of injury (OR = 1.5-2.5) compared to those with superior aerobic fitness (62). With this evidence in mind, appropriately planned conditioning should be included within the injury prevention plan in order to improve overall fitness levels and reduce the burden of fatigue upon the hamstrings. For team sport athletes, this can include maximal aerobic speed training (MAS) (8). This can be prescribed at increased percentages of an individual's MAS across stages 1-3 (outlined in figure 1) (8), after which sport specific conditioning (i.e., small sided games in soccer) can be implemented during the in-season period . In non-running-based sports, fitness can be developed through sport-specific conditioning. For example, it has been recommended that dancers can build cardiorespiratory fitness through utilising dance movements with appropriate work:rest time periods (115).

High Speed Running

The monitoring of running loads, and more importantly in the case of HSI prevention, high-speed running loads is common within sports performance (28,38,48,61,63,85). All running based training, and particularly that covered above 24km/h, should be carefully monitored to prevent spikes in training load and to ensure that the athlete has been exposed to appropriate training doses that may provide a preventative effect upon HSI occurrence (28,38,48,61,63,85). The inclusion of conditioning-based drills and supplemental maximal velocity training should be informed by the data collected from this monitoring process.

Plyometrics

Plyometrics are often included within athletic training programmes; however, their potential role in HSI prevention is often over looked. Previously, plyometric based exercises, including: unilateral and bilateral sagittal plane hurdle hops, frontal plane hurdle hops, 180° hops and split squat jumps, have been shown to recruit the hamstring musculature (98). Furthermore, due to the nature of plyometric exercises, they are likely to produce hamstring muscle actions at high velocities throughout the stretch shortening cycle (105). Therefore, they have the potential to stimulate muscle actions which are similar to those reported during the mechanism of injury associated with high speed running (105).

Tsang and DiPasquale, (104) implemented a six week plyometric training programme where subjects performed the intervention three times per week. Their findings highlighted increases in hamstring strength alongside maintaining quadriceps strength; thus, improving the Q:H ratio (104). Additionally, Vissing et al. (111) demonstrated significant ($p < 0.001$) increases in hamstring cross-sectional area ($6.7 \pm 1.8\%$) following a 12 week plyometric training intervention. However, their results should be viewed with an element of caution, as the subjects were classified as "untrained" and therefore it could be hypothesised that any training stimulus would have promoted a positive effect.

The plyometric exercises included in stage one, as well as the drop land in stage 2, of both prevention programmes are aimed at developing optimal landing mechanics, which should be established before progressing to exercises of greater intensity and complexity (106). The additional exercises within figure 1 are programmed with a bias towards horizontal force production, in order to replicate similar movement vectors to that during high speed running. The additional exercises within figure 2 are focused on developing overall plyometric ability, but may be adapted to suit each individual sport.

** INSERT FIGURES 1 & 2 ABOUT HERE **

Figure 1. Potential evidence based HSI prevention programme focusing on type I strains.

Figure 2. Potential evidence based HSI prevention programme focusing on type II strains

Conclusion

Within sports performance, HSI are highly prevalent and incur high reinjury rates. Consequently, this leads to athletes missing extended periods of the competitive season, which can have a detrimental effect on both the performance and finances of sporting organizations. Although HSI commonly occur during high-speed running activities, practitioners should be aware that a variety of injury mechanisms exist. Furthermore, a multitude of possible contributing risk factors for HSI have been well documented within the literature, highlighting the need for injury prevention programmes to be multifaceted in nature.

These programmes should include an appropriate warm-up, where other elements of the injury prevention plan (i.e., flexibility) can be included. Eccentric strength training, both bilateral (Nordic curl, stiff leg-deadlift) and unilateral (single leg-stiff leg deadlift, single leg slider curl, Askling glider and diver), should be included to improve hamstring strength and reduce muscular imbalances. Alongside this, the RFESS should be considered within HSI prevention programmes due to its reported benefits to hamstring recruitment. Conditioning drills, either in the form of MAS or sport specific conditioning, should be incorporated to improve overall fitness levels and reduce the burden of fatigue. For running based athletes, careful monitoring of high-speed running loads should be initiated and used to inform training load to ensure that athletes are exposed to an appropriate training dose. Finally, plyometrics should be included that may have the potential to activate the hamstrings at high velocities. These should begin by focusing on correct landing mechanics, before progressing to higher velocity exercises. In the case of running based athletes, it may be prudent to focus upon exercises that require athletes to produce horizontal force.

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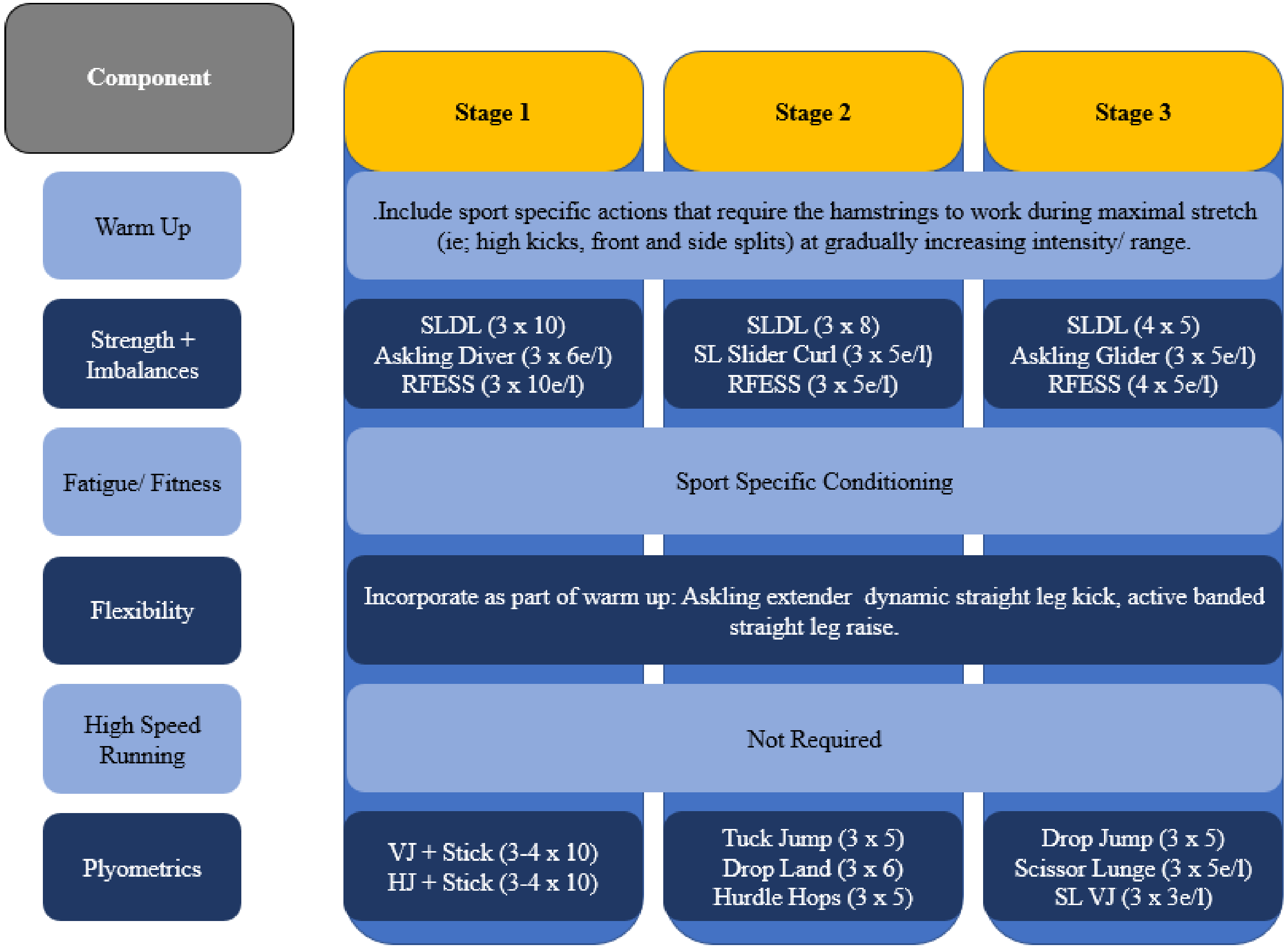
Table 1. Hamstring injury incidence and time lost across a number of sports.

Author(s)	Subjects	Study Length	Hamstring Injury Definition	Injury Incidence	Time Lost
Brooks et al. [16]	546 professional rugby union athletes.	2 seasons.	Any injury that prevents a player from taking full part in all training or match play activities for a period >24 hours.	5.6 per 1000 player hours.	Total of 1176 days. 151 days per 1000 player hours.
Ekstrand et al. [29]	23 UEFA soccer clubs.	7 seasons.	Any injury which prevents a player being able to fully participate in training or match play.	7 in 25 players suffer a hamstring strain.	12% of severe injuries (>28 days lost) were hamstring strains.
Orchard et al. [76]	37 professional Australian footballers.	1 season.	Clinically diagnosed and caused a player to miss match playing time. Minor injuries where only practice time were missed were not included.	6 injuries.	Average 2.5 matches missed. Range 1-6.
Orchard et al. [77]	Elite cricketers.	20 years.	Diagnosis by medical personnel.	Match injury incidence 22.5 per 1000 team days.	Not reported.
Ekstrand et al. [31]	36 soccer clubs	13 seasons.	Any injury which prevents a player being able to fully participate in training or match play.	1614 total injuries. 1.2 injuries per 1000 player hours.	Mean time lost: 17 days
Dalton et al. [26]	25 NCAA sports teams.	5 academic years.	An injury identified by an athletic trainer that occurred during NCAA-sanction practice or match.	1142 total injuries. 3.05 per 10,000 hours.	37.7% time loss <24 hours. 6.3% time loss >3 weeks.
Woods et al. [114]	91 professional soccer clubs.	2 seasons.	An injury sustained in normal competition or training which prevented a player from taking part in normal training and competition for >48 hours.	796 total hamstring injuries (749 were strains); 12% of total injury occurrence. Average of 5 hamstring strains per club per season.	Average 18 days and 3 matches per injury. Clubs can expect 90 days and 15 matches missed per season.
Petersen et al. [79]	374 elite soccer players.	12 months.	Any self-reported posterior thigh pain from training or competition.	3.4 hamstring injuries per team per season.	Average 21.5 days per injury.
Askling et al. [3]	98 student dancers.	Retrospective study: unlimited length.	Self-reported pain to the posterior thigh.	51% reported suffering injury.	Range from 2 weeks to 80 months.
Gabbe et al. [36]	222 elite Australian footballers.	1 season	An injury causing an athlete to miss at least one game.	14% sustained an injury.	Not reported.
Opar et al. [72]	48,473 track and field athletes.	3 years.	Incident causing acute pain to posterior thigh which resulted in cessation from competition. Positive clinical examination upon follow up.	118 injuries. 24.1% of all injuries.	Not reported.

Component	Stage 1 (Pre-season) Weeks 1-4	Stage 2 (Pre-season) Weeks 5-8	Stage 3 (Pre-season) Weeks 9-12	Stage 4 (In-Season) Maintenance
Warm Up	Incorporate elements of FIFA 11+ programme. Gradually increment running speeds to maximal velocity. In kicking sports (such as soccer), gradually increment kicking distances from short to long.			
Strength + Imbalances	Nordic Curl (2 x 5) SL SLDL (3 x 6e/l) RFESS (3 x 10e/l)	Nordic Curl (3 x 5) SL Slider Curl (3 x 5e/l) RFESS (3 x 5e/l)	Nordic Curl (4 x 5) Askling Glider (3 x 5e/l) RFESS (4 x 5e/l)	Nordic Curl (2 x 5) Askling Glider (2 x 5e/l) RFESS (3 x 5)
Fatigue/ Fitness	Conditioning @ 100% MAS	Conditioning @ 110% MAS	Conditioning @ 120% MAS	Sport Specific Conditioning
Flexibility	Incorporate as part of warm up: Askling extender dynamic straight leg kick, active banded straight leg raise.			
High Speed Running	Monitor high speed running loads to ensure adequate exposure and avoid spikes. Include supplemental exposure to maximal velocity (sprint) running if required.			
Plyometrics	VJ + Stick (3-4 x 10) HJ + Stick (3-4 x 10)	Multiple HJ (3 x 5) Drop Land (3 x 6) SLB (3 x 20m)	Drop Jump (3 x 5) H Bounding (4 x 20m) Scissor Lunge (4 x 5e/l)	Drop Jump (2 x 5) H Bounding (2 x 20m) Scissor Lunge (2 x 5e/l)

Key: SL = single leg, SLDL = stiff-leg deadlift, MAS = maximal aerobic speed, VJ = vertical jump, HJ = horizontal jump, m = metres, SLB = straight leg bound, H = horizontal, e/l = each leg, RFESS = rear foot elevated split squat.

Figure 1. Potential evidence based HSI prevention programme focusing on type I strains.



Key: SL = single leg, SLDL = stiff-leg deadlift, VJ = vertical jump, HJ = horizontal jump, m = metres, e/l = each leg, RFESS = rear foot elevated split squat.

Figure 2. Potential evidence based HSI prevention programme focusing on type II strains.