Chapter

Strategic Prevention Program of Hamstring Injuries in Sprinters

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Abstract

Enhancing the functionality of the hamstring is an important matter for sprinters in improving their performance. Sprinters show almost the highest incidences of hamstring injuries as compared with other athletes. For sprinters and their coaches, prevention of hamstring injury is a prime concern along with improved their performance. To prevent hamstring injuries in sprinters, injury, incidence, mechanisms, and risk factors need to be taken into consideration, and a strategic program based on evidence needs to be implemented. A combination of three factors: agility, strength, and flexibility, is a good contributor to preventing muscle injuries in sprinters. Simultaneously, the training programs need to take into consideration the conditioning for muscle fatigue depending on a sprinter's abilities. It may be important for coaches, trainers, and sports doctors to encourage sprinters for stopping training to monitor the degree of fatigue objectively and subjectively and to avoid the risk of injury. Future establishment of a hamstring injury-prevention program will be achieved by building a support system for programs with tactics and strategies. These programs are based on the accumulation of data via cooperation among coaches, researchers, trainers, and sports doctors.

Keywords: hamstring injury, prevention program, sprinters

1. Introduction

In maximal sprinting, stride frequency plays a more decisive role than stride length does [1]. In addition, the large negative power for eccentric contraction of knee flexors (hamstrings) and the large positive power for concentric contraction of hip extensors contribute to high stride frequency, enabling the sprinter to run at higher speeds [2, 3]. Therefore, enhancing the functionality of the hamstrings is important to improve the performance of sprinters [2–4].

Sprinters nearly have the highest incidences of hamstring injuries compared with other athletes [5]. For sprinters and their coaches, the prevention of hamstring injuries is a primary concern alongside improving performance. However, clarifying the causal relationship between the cause and occurrence for hamstring injuries is challenging, as well as accumulating evidence for preventing hamstring injuries [6].

To prevent hamstring injuries in sprinters, injuries, incidences, mechanisms, and risk factors should be considered, and a strategic program based on evidence should be implemented. The construction of modified prevention systems and the use of the latest technology will reduce hamstring injuries in sprinters. This contributes to the improvement of their performance.

2. Structure of the hamstrings

The hamstring muscle group consists of three major muscles of the posterior thigh, namely the semitendinosus, semimembranosus, and biceps femoris (long and short head) [7–9]. The long head of the biceps femoris, semitendinosus, and semimembranosus have a biarticular formation where they cross the knee and hip joints. The short head of the biceps femoris arises from the femur and inserts at the fibula head, making it a uniarticular muscle that crosses only the knee joint (**Figure 1**) [7–9].

Regarding the long head of the biceps femoris, the medial part of the ischial tuberosity represents the origin of the proximal tendon, while the distal insertion is on the lateral surface of the fibula head [7–9]. The semitendinosus has the same origin as the previous muscle; however, it is inserted on the medial tibial surface [7–9]. The proximal tendon of semimembranosus also has the same origin but originates from the lateral part, and the posterior aspect of the medial tibial condyle represents the distal insertion of the muscle [7–9].

The biceps femoris is the only component of the hamstring muscle group with dual innervation. The long head of the biceps femoris, semimembranosus, and semitendinosus are all innervated by the tibial branch of the sciatic nerve. The short head of the biceps femoris is innervated by the peroneal portion of the sciatic nerve.

Thus, the biceps femoris is considered a "hybrid" muscle [10] that has two heads with different origins and dual innervation. This feature may be a predisposing factor for hamstring injuries [11]. In research for elite track and field athletes in the British Athletics World Class [12], an isolated injury to the long head of biceps femoris was the most frequently occurring hamstring muscle injury (70%). Most injuries

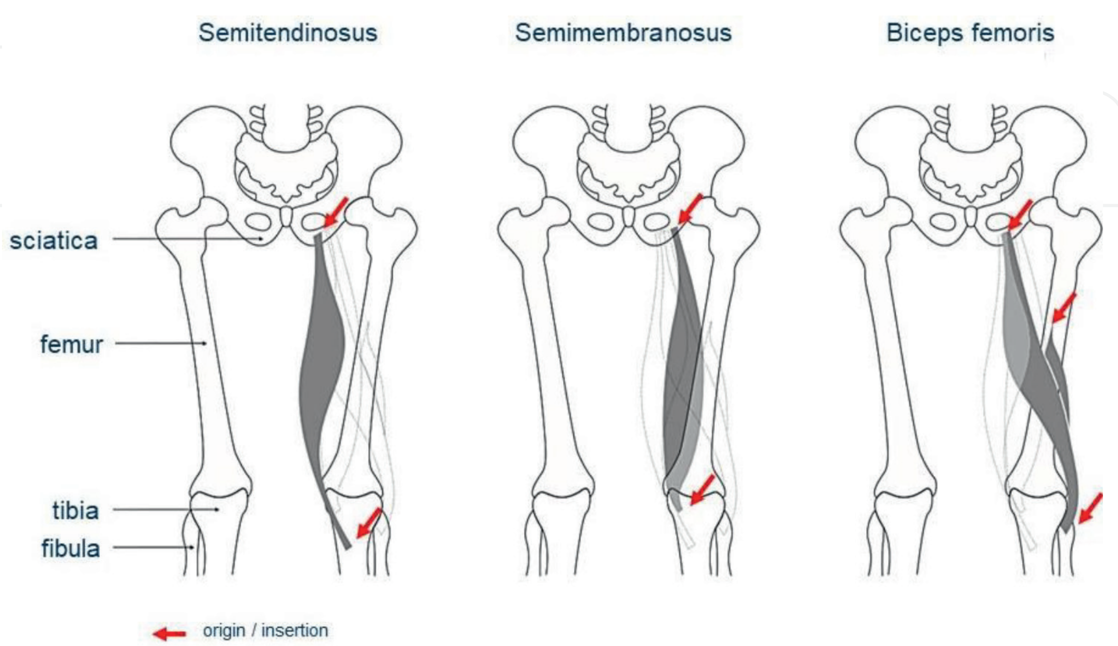

Figure 1.
Structure of the hamstrings.

occurred in the distal third of the hamstring (43%), with 31% in the proximal third and 26% in the central third.

The British Athletics Muscle Injury Classification is a reliable MRI-based classification system that categorizes the patients according to the injury site: myofascial (class a), muscle-tendon junction (class b) or intratendon injury (class c), and a numerical grading system (0–4) based on the extent of injury [13].

The isolated function of the hamstrings is to generate knee flexion and hip extension. During more integrated or dynamic muscle actions such as the stretch-shortening cycle [14–16] on sprinting, the hamstrings help in stabilizing the lumbopelvic hip complex and the knee joints [17, 18]. As such, hamstrings have unique structures (anatomy) and functions (physiology).

3. Biomechanics of high-speed running regarding hamstring injuries

A complete running cycle, that is, symmetrical and linear movement [19] in a sprinter includes two main phases: the contact phase in which the foot is in contact with the ground and the swing phase in which the foot is not in contact with the ground. Two main phases can be further divided into subphases: early contact (braking), late contact (population), early swing (thigh forward), and late swing (thigh back) (**Figure 2**) [19, 20].

In sprinters, hamstring injuries occur during high speed running, most likely because of the hamstrings along with its complex actions. The mechanism underlying this is attributed to its feature of being a biarticular muscle [14, 21], and its double innervation [22] works very rapidly to generate a large amount of power.

As hamstrings muscles are mainly hip extensors, they work in the late swing phase of sprinting to concentrically and quickly get the thigh back [2, 4] while acting as knee flexors to eccentrically decelerate the forward swing of the lower leg [2, 4, 14]. In the early contact phase, the hamstrings apply concentric action as knee flexor and hip extensor muscles to reduce the loss in running speed, which shifts the body's center of gravity forward smoothly [14, 23]. To maximize running speed during sprinting, the hamstrings must generate a large amount of power in these phases [2, 3, 24].

From the late swing phase to the early contact phase during full-speed running, the hamstrings must rapidly switch from eccentric contractions to concentric

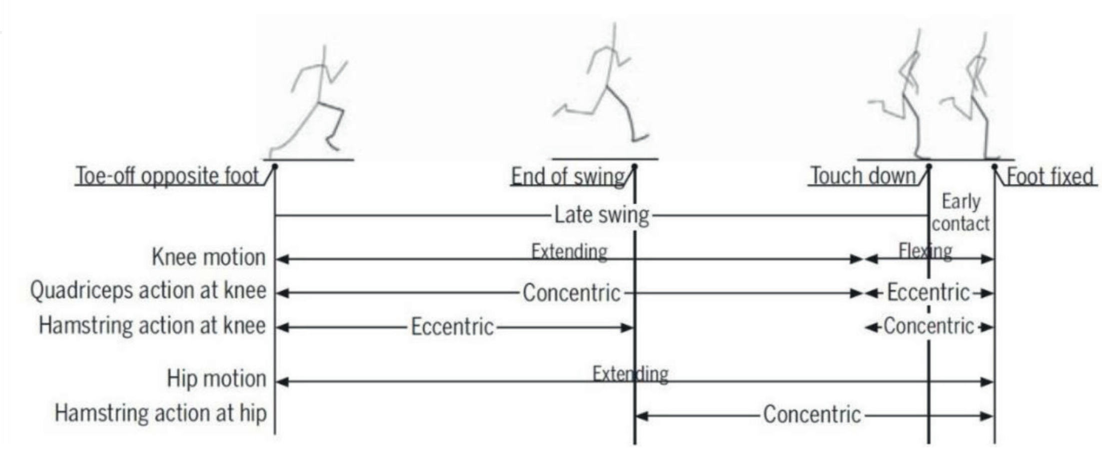

Figure 2.
Dominant quadriceps and hamstring contraction modes (the muscle contractions are concentric and eccentric) in the late swing and early contact phases of sprinting [19].

contractions (stretch-shortening cycle) [14–16] while under the influence of the contractile activity of the quadriceps femoris muscle [25]. These actions generate high forces, which have been postulated to be related to hamstring injuries [15], are commonly seen in sprinters [26, 27].

Most researchers investigating the role of the hamstring during sprint argue that the late swing phase is likely to be the point in the running cycle at which the hamstrings are most susceptible to injuries [18, 28–32]. A few researchers speculated that the early contact phase would be the highest risk point of sprint [4, 24]. Most of the injuries occur during the late swing and early contact phases of running.

4. Presenting risk factors regarding hamstring injuries

In 1985, Agre [33] discussed hamstring injuries occurring while running or sprinting. He listed several possible factors related to hamstring injuries, which are widely accepted in the research and clinical fields; they include (1) inadequacy of muscle flexibility, (2) muscle strength and/or endurance, and (3) warm-up and stretching before activity; (4) dys-synergic muscle contraction; (5) awkward running style; and (6) resumption of activity before complete rehabilitation.

In a theoretical model, Worrell [34] suggests that the increase in the risk of hamstring injuries is because of a mix of abnormalities related to strength, flexibility, warm-up method, and fatigue. Devlin [35] posits a threshold above which the number of risk factors contributes to injuries. Therefore, some factors are potentially more capable of predicting injuries than others.

Based on the results of practical research conducted by Sugiura et al. [6], strength deficits, lack of neuromuscular control, and lack of flexibility contribute to the incidence of hamstring injuries. However, the effects of each of the three factors on hamstring injuries have not been examined. This chapter provides an overview of factors 1–3 (**Table 1**).

4.1 Inadequate muscle strength

Many studies have examined the causes of hamstring injuries related to leg muscle strength. Previous studies have emphasized the relationship between hamstring weakness during eccentric contraction and muscle injuries [15, 16, 36].

However, in 2008, Sugiura et al. [37] reported that muscle weakness during eccentric contraction of the hamstring (hip extensor) can also contribute to hamstring injuries. Whichever it is, insufficient hamstring strength, left-to-right muscle imbalance, and decreased hamstring strength relative to quadriceps strength (H/Q ratios) are thought to cause hamstring injuries.

Cause		**Result**
One and/or more of risk factor	Trigger	Onset
Inadequate muscle strength Ds-synergic muscle contraction Inadequate flexibility of muscles	High-speed running	Hamstring injuries

Table 1.
Cause and result for hamstring injuries.

Insufficient hamstring strength weakens the contraction force and causes the thigh back to swing quickly in late swing phase. Moreover, in the early contact phase, the hip joint extension torque could not be exerted sufficiently. This results in excessive eccentric load on the hamstrings, which was presumed to cause hamstring injuries.

4.2 Dys-synergic muscle contraction

Hamstrings are involved in leg movements in various sports events. Among them, in sprinting, which requires high speed, the hamstrings contribute significantly to performance compared with other events.

During sprinting, the hamstrings are not affected by the activity of the quadriceps femoris. Sprinters should respond rapidly from eccentric contraction to concentric contraction (stretch-shortening cycle) [14–16] from the late swing phase to the early contact phase. Sprinters exert more power in split second and achieve higher speeds by using the stretch-shortening cycle. Neuromuscular coordination plays an important role in these mechanisms. From the late swing phase to the early contact phase, if there is ataxia, such as changes in the contraction strength of the hamstring or dys-synergic muscle contraction, the hamstring injuries will become onset [33].

4.3 Inadequate flexibility of the muscles

As the flexibility of the hamstring decreases, the "knee flexion angle–torque relationship" shifts to the left (37). This indicates that the hamstring length at the peak torque is shorter. In the tension-length relationship of the muscles, shortening optimal for muscle length means that the resistance to the eccentric load is low. Brockett et al. [38] (2001) concluded that a shorter muscle length at peak torque is a risk factor for hamstring injuries.

Sprinting involves moving leg joints through a large range of motion as much power as possible. The lack of hamstring flexibility will lead to hamstring injuries.

5. How to prevent hamstring injuries

In ball sports, hamstring injuries occur when turning sharply or cutting [39], whereas in sprinting, injuries often occur while running at high speed [16, 33]. Two types of hamstring injuries, defined by the injury mechanism, have been described as stretch- and sprint-type hamstring injuries [40]. Stretch-type hamstring injuries occur on movements involving a combination of extreme hip flexion and knee extension such as kicking and maneuvers, whereas sprint-type hamstring injuries occur during maximal or near-maximal running movement [41]. Therefore, hamstring injury types on ball sports players are of stretch and sprint complex types.

To obtain useful information for a hamstring injury prevention program, it is desirable to conduct research on sprinters for track and field. A hamstring prevention program for sprinters could become a standard prescription for many events, including ball sports.

5.1 Onset of hamstring injuries related to hamstring weakness

The muscle strength of the hamstrings, hip extensor, and quadriceps was measured and related to the subsequent occurrence of hamstring injuries over a 1-year period of a prospective study [37]. Isokinetic testing was performed on 30 male elite sprinters for the assessment of hip extensors, quadriceps, and hamstring strength. The methods used for testing muscle strength simulate the specific muscle action during the late swing and early contact phases while sprinting. The strength of the hip extensors, quadriceps, and hamstrings, as well as the H/Q ratios, was compared between uninjured and injured sprinters.

During the research period, a hamstring injury in one lower limb occurred in six sprinters (10.0% of 60 lower extremities). All injuries were sustained while sprinting. The participants were divided into the uninjured group (comprised of 48 lower limbs in 24 participants) and injured group (comprised 12 lower limbs in six subjects).

At a speed of 60/s, the torque of the hamstrings measured eccentrically about the knee and concentrically about the hip was significantly lower for the injured lower limb than for the uninjured limb (**Figure 3**). The differences in H/Q ratios between the uninjured and injured lower limbs in the injured group were solely attributable to the differences in hamstring strength. These results suggest that the weakness of the hamstrings and possibly hip extensors is a cause of injuries (**Figure 4**).

The onset of hamstring injuries in elite sprinters was related to hamstring weakness during eccentric contractions across the knee and concentric contractions across the hip. The identification of sprinters with unilateral weakness of the hip extensors and knee flexors may reduce the incidence of hamstring injuries.

This study focused on the relationship between muscle strength and the occurrence of hamstring injuries. Other factors such as agility and flexibility may have contributed to the occurrence of hamstring injuries.

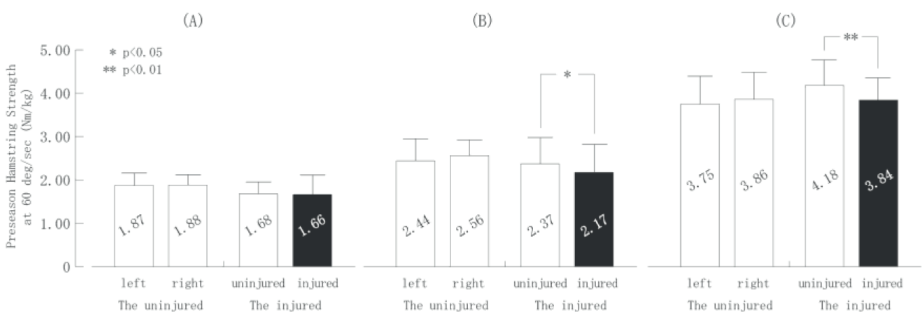

Figure 3.
Mean (SD) preseason hamstring strength for sprinters who did not experience the hamstring strain (the uninjured: n = 24) compared with sprinters who subsequently sustained the hamstring strain (the injured: n = 6). (A): Knee flexion-concentric (B): Knee flexion-eccentric (C): Hip extension-concentric.

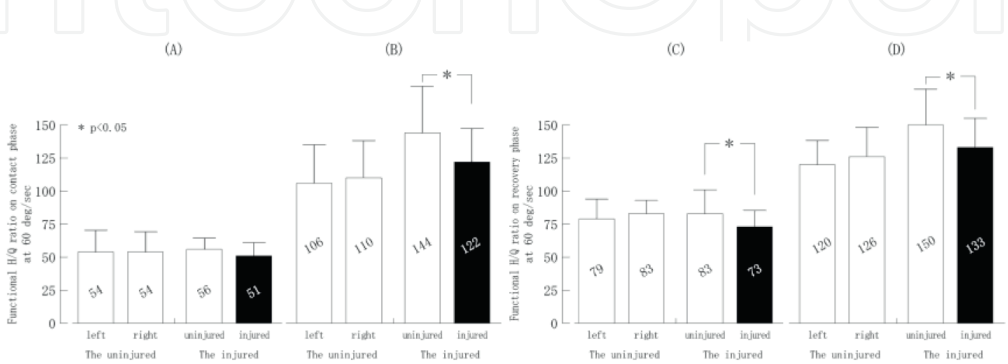

Figure 4.
Mean (SD) preseason functional H/Q on contact (A), (B) and recovery (C), (D) phase for sprinters who did not the hamstring strain (the uninjured: n = 24) compared with sprinters who subsequently sustained the hamstring strain (the injured: n = 6). (A): Knee flexion-concentric/knee extension-eccentric (B): Hip extension-concentric/knee extension-eccentric (C): Knee flexion-eccentric/knee extension-concentric (D): Hip extension-concentric/knee extension-concentric.

5.2 Effects of prevention program on hamstring injuries

A total of 613 collegiate male sprinters employed submaximal/maximal running for several runs and supramaximal running for a few runs throughout their 24 years of training [6, 19, 25]. The hamstring injury prevention program had become the most effective strategy in 24 years. The program was divided into three periods: period I that covered four seasons (1988–1991), period II that covered eight seasons (1992–1999), and period III that covered 12 seasons (2000–2011).

5.2.1 Strategic combination programs to prevent hamstring injuries

The injury prevention program for sprinters has evolved over time to reflect the current most effective strategies for preventing hamstring injuries (**Table 2**). New programs and equipment were developed and introduced for the Olympic Games of Seoul, Barcelona, and Sydney. As a result, the number of programs has increased and prevention programs evolved [6, 19, 25].

For an appropriate prevention program, the coach modified the program through trial and error while investigating causative factors. Consequently, the program aimed to improve neuromuscular function, muscle strength, and dynamic flexibility.

Period I only consisted of performing concentric hamstring strengthening with help of a traditional leg curl weight machine. Period II is similar to the period I program but with additional agility training, including ladder and mini-hurdle exercises. To allow a concentric hip extension exercise, a newly developed weight machine was introduced in the middle of period II. In period III, eccentric hamstring strengthening exercises (Nordic hamstring exercise [42, 43], glute-ham raise exercises, [44], and dynamic stretching exercises) were added in addition to the programs implemented in period II.

Objective and method	Action and/or Motion (Load)	Period		
		I	II	III
Strength				
Weight macine	Knee flexors concentrically (leg curl) (3/5–4/5 of body weight × 10 repetitions × 3–5 sets)	●	●	●
	Hip extensors concentrically (hip extension) (4/5–5/5 of body weight ×10 repetitions × 3–5 sets)		●	●
Body weight	Knee flexors eccentrically (Nordic hamstring exercise) (lean forward slowly × 30–60 seconds × 5 sets)			●
	Knee flexors eccentrically and hip extensors/knee flexors concentrically (glute-ham raise) (lean forward, downword, and upward × 10–20 repetitions × 5 sets)			●
Agility				
Ladder	5 types of fast stepping in all directions (10 m × 4 repetitions)		●	●
Mini-hurdle	4 types of one and/or both leg(s) with fast stepping (10 hurdles × 4 repetitions)		●	●
Flexibility				
Dynamic stretching	3 types of stretching for muscles around hip joint (20 m × 1 repetitiion)			●

Table 2.
Description of the standard preventive program for hamstring injuries.

The sprinters performed all program parts according to the loads, actions, and motions designated for each program, as mentioned in **Table 1**. In each case, the program used was modified according to the coach's judgment, considering the condition of the sprinter. Strength training was considered as a part of the weight training, and agility/flexibility training was performed during warm-ups.

5.2.2 Prescription for volume/quality of overall sprint training throughout the year

Figure 5 presents the standard program with usual and special training arranged for the overall sprint training applied throughout the year. Training program was divided into six phases: recovery, basic training, preseason, first season, interseason, and second season.

Excluding the recovery phase, the regular training for submaximal and maximum running was completed in five phases. In contrast, specialized training for supramaximal running was carried out within a short time, weeks, in four phases, eliminating the recovery and basic phases. With modifications to volume and quality, three types of running—submaximal, maximum, and supramaximal—were carried out throughout the year, except for the recovery phase.

5.2.3 Submaximal and maximal running for volume training

Submaximal and maximal running types are types of volume training (**Figure 5**). Submaximal and maximal running types have sufficient volume to cause overload,

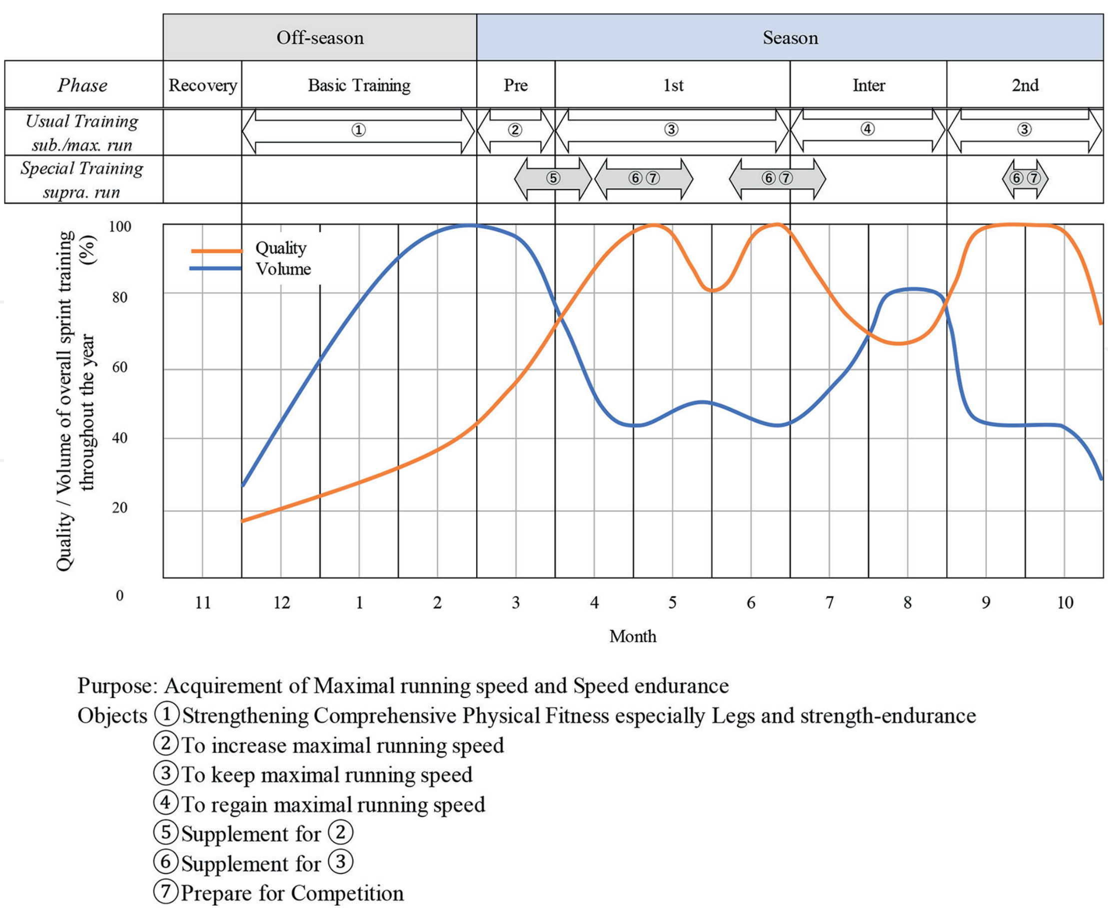

Figure 5.
Concepts of overall sprint training program throughout the year.

Training Contents	
BasicTraining:①	**Pre-season:②**
30 minutes build up every 10 minutes for Cross–Country 100 m at 70% OR 200 m at 60% 10–20 repetition for Up Hill Running 100–150 m 10 kg – Weights x 5 repetitions on Sled for Resistance Running. 200–300 m at 60% 10 repetitions 250–400 m at 60% 10 repetitions	50–100 m 10 kg–Weights x 5 repetitions on Sled for Resistance Running 150–200 m at 80–90% 3 repetition x 2–4 sets 300 m at 70–80% 5 repetitions 1–2 sets
1st and 2nd–season:③	Inter–season:④
50–100 m 5 kg–Weights x 2 repetitions on Sled for Resistance Running 30–60 m at 90–100% 5 repetitions for Start Dash and (100 m at 95%, 150 m at 95%, 200 m at 90%) 1–2 sets 30–60 m at 90–100% 5 repetitions for Start Dash and (100–120 m at 95%) 3–5 repetitions, 50 m at a constant tempo for Skip x 5 repetitions 30–60 m at 90–100% 5 repetitions for Start Dash and (200 mat 90%, 400 m at 90%) 1–2 sets 30–60 m at 90–100% x 5 repetitions for Start Dash and (250–300 m at 90%) 3–5 repetitions, 50–100 m at a constant tempo for Skip 3–5 repetitions	50–100 m 5 kg Weights 2 repetitions on Sled for Resistance Running 150 m at 90% 3 repetitions 2–3 sets (150–200 m at 85%) 5 repetitions, 50 m at a constant tempo for Skip x 5 repetitions 250–300 m at 90% 3 repetitions 1–2 set (200–300 m at 85%) 3–5 repetitions 50–100 m at a constant tempo for Skip 3–5 repetitions

**The sprinters practiced as a sprint training of either content during each phase.*
**Percentage represents the rate of increase in running velocity.*

Table 3.
Contents of usual sprint training for submaximal and maximal running.

followed by acute fatigue. Usual training helps sprinters achieve submaximal and maximal running speed by repeated acute fatigue, which causes an adaptive response. Submaximal running and maximal running were practiced with independent efforts (non-assisted) or under an increased workload, such as running uphill or using a sled (resisted). Therefore, the usual training for submaximal and maximal running comprises several runs (**Table 3**).

5.2.4 Supramaximal running for quality training

Supramaximal running is a type of quality training. Therefore, this training was conducted at that point in the overall sprint training schedule when the quality was improved or when it was high. Moreover, the total volume of training decreased (**Figure 5**).

Supramaximal running for special training was practiced with assistance in tow training. Tow training was performed using a towing machine (**Figure 6**) and a rubber tube [6, 25, 45]. The rate of increase in the velocity of a sprinter is up to 103–107% during supramaximal running [45–50]. In sprinters, the generated higher force with overspeed training is postulated to be related to hamstring injuries in supramaximal running. The researchers and coaches have highlighted issues related to hamstring injuries [50–52].

On the other hand, muscle fatigue is a risk factor for hamstring injuries [33, 53, 54]. Therefore, supramaximal running was performed following a day off or on an individual practice day when the lowest muscle fatigue was expected. Each sprinter was involved in 2–5 runs/day for 15–25 days/season. In reality, over a season, the number of runs per sprinter ranged from 20 to 30. Special sprint training for supramaximal running includes a few runs (**Table 4**).

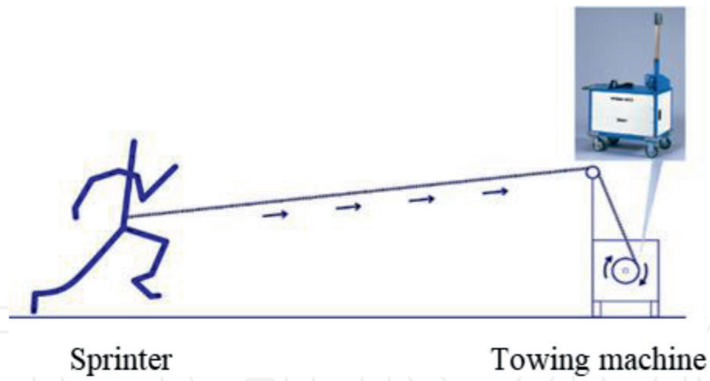

Figure 6.
Supramaximal running in towing system.

Training Contents	
Pre-season and 1 st season:⑤	**1st, 2nd and Inter-season:⑥,⑦**
50–100 m at 105% × 3–5 repetition	50 m at 105–110% × 3 repetition 50 m at 105–110% × 1

**The sprinters selected the distanse, the rate of increase in running velocity and numbers in towing during each phase.*

Table 4.
Contents of special sprint training for supramaximal running.

5.2.5 Effective strategic combination programs to prevent hamstring injuries

The injury risk increases in fatigue conditions [53, 54]. Fatigue conditions may lead to dys-synergic contraction of different muscle groups, lack of muscle strength, and decreased muscle endurance causing hamstring injuries [33]. Therefore, supramaximal runs were practiced with fewer repetitions because of the fatigued states of the sprinters. The effective strategic combination of prevention programs, agility, strength, and flexibility could reduce the incidence of hamstring injuries (**Figure 7**).

Agility program allows learning the rapid motion needed to cope with supramaximal running. Sprinters who practiced using ladders and mini-hurdles exhibited rapid stepping equivalent to or faster than the stride frequency that had been observed during supramaximal running [6]. Motion training at a high level, such as supramaximal running, which requires a quick sprinting motion, incorporates the learning of new muscle recruitment patterns that involve peripheral sensory input. The muscle synergy adapted to high-level sprinting motion was likely acquired by all sprinters using ladders and mini-hurdles. Thus, the incidence of hamstring injuries decreased during supramaximal running.

Strength program applies an eccentric load to the hamstring through the trunk position at the injury position. During supramaximal training, eccentric strength program worked well against load on the hamstrings. The incidence of hamstring injuries during period III with eccentric strength program decreased compared with the period I. All sprinters strengthened their hamstrings with leg curls, hip extensions, and two types of modified Nordic hamstring exercises. This likely decreased the incidence of hamstring injuries during supramaximal running.

With dynamic stretching, the neuromuscular system becomes a softer musculotendinous system with increased length and allows the performance of larger

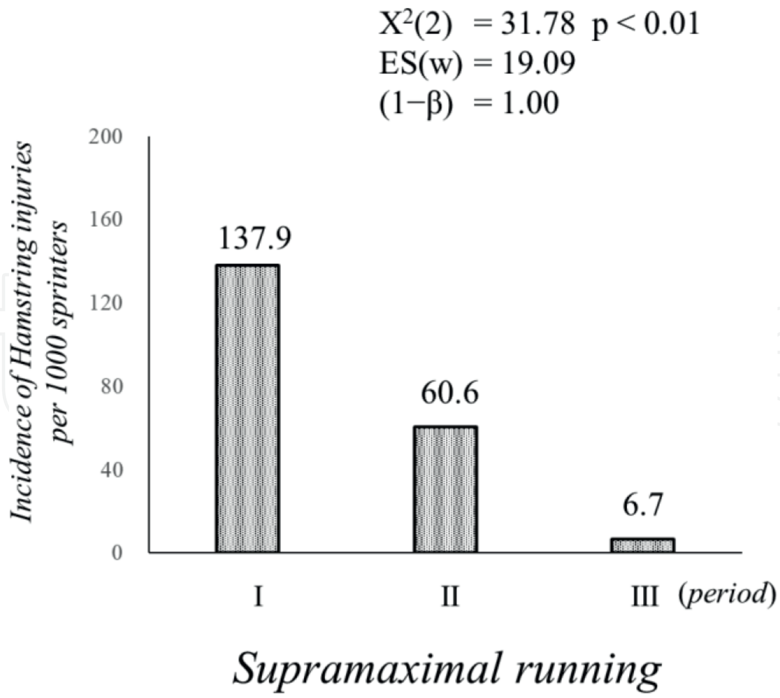

Figure 7.
Hamstring injury rate during supramaximal running.

movements [55]. The goal of dynamic stretching is to provide flexibility in the lumbopelvic region muscles. Moreover, it adapts the hip joint to a mobile state where dynamic flexibility is secured. The hip joint movement adapted to supramaximal running may be acquired by stretching the hamstring, quadriceps femoris, and other muscles during active joint movements. Dynamic stretching is conjectured to function effectively in preventing hamstring injuries while assisting athletes to perform at a high level. Dynamic stretching is potentially effective in preventing hamstring injuries in supramaximal running.

By implementing three hamstring injury programs simultaneously—agility, strength, and flexibility—we can demonstrate their relative effects on injury reduction. Therefore, investigating what program or combination is the most effective is necessary. The combination of prevention programs, agility, strength, and flexibility, reduced the incidences of hamstring injuries. The prevention program was effective in supramaximal running because only a few runs were made due to the fatigued states of the sprinter.

5.2.6 Muscle fatigue condition: a crucial risk factor for hamstring injuries

Usual training has sufficient volume and intensity to cause overload, followed by acute fatigue [19]. The yearly summation of several training programs will result in greater fatigue and subsequent supercompensation response [56]. This adaptive response will leave the participant in a healthier state than the previous state [56]. Therefore, usual sprint training for submaximal and maximal running contains several runs. Even if the program could prevent hamstring injuries during submaximal/maximal running with a sufficient volume for several runs in usual training, the incidence of hamstring injuries did not decrease (**Figure 8**).

Fatigue has an impact on muscle activation and function, including lumbopelvic control, knee stability, leg stiffness, and muscle-tendon unit energy transfer [53].

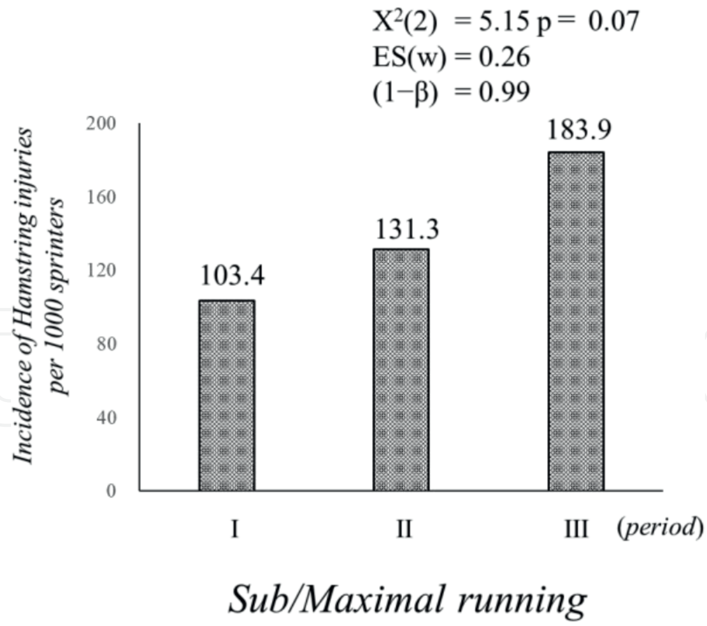

Figure 8.
Hamstring injury rate during submaximal and maximal running.

Alterations in running kinematics, such as the "Groucho position" caused by fatigue, minimize exercise efficiency while elevating force moments. Additionally, it is associated with increased stress on contractile muscle units. Theoretically, there is a risk of damage to the hamstrings [53].

In usual training, which causes muscle fatigue following several runs, the physical performance of increased strength, agility, and flexibility with prevention programs may not have positive effects on hamstring activation and function. Hamstring injury prevention program had no effect on the fatigued hamstrings, muscle groups, hip extensors, and knee flexors.

6. Practical applications

The combination of three programs, agility, strength, and flexibility contributes well to sprinters for the prevention of muscle injuries. Moreover, the prescription should consider conditioning depending on sprinters.

In running-based training, clarifying and considering the time set for a distance are important to not only improve performance but also prevent injuries. In usual training for several runs, it is difficult to clear the set time because of fatigue caused by repeated running. At that time, "Groucho running" patterns may be observed because of poor muscle activation and function [53]. A sprinter unable to clear the time set by the coach will not achieve the training purpose. Therefore, for running-based training, sprinters should carefully monitor the running time and inform the training load so that the athletes are objectively exposed to the appropriate training volume [54].

Furthermore, it is also important to subjectively consider fatigue. Coaches should check the physical condition (degree of fatigue) of the sprinters before training using a numerical value (e.g., visual analog scale) to quantify the physical condition of the sprinters (**Table 4**). Sprinters should measure body temperature, heart rate, and flexibility in the morning daily and translate their values into subjective physical condition on a scale

Subjective Scale	Physical Condition
1	Very Bad
2	Bad
3	Neither Bad or Good
4	Good
5	Very Good

Sprinters measure body temperature, heart rate, and flexibility in the morning on every day, translate their values into subjective physical condition on a scale of 1–5.
Sprinters rate themselves scale 1 or 2 when they experience the muscle pain or tightness. Then, the coach makes sprinters stop training or practice training with quality and volume adjustment.
Sprinters often rate themselves scale 3 or 4.
Sprinters rate themselves scale 5 that is led by peaking for a match.

Table 5.
Subjective scale for physical condition for sprinters.

of 1 (very bad) to 5 (very good). If sprinters rate themselves as a scale 1 or 2 when they experience muscle pain or tightness, then their coach can make sprinters stop training or practice training with quality and volume adjustment. Sprinters often rate themselves as scale 3 or 4. Sprinters rate themselves as 5 that is led by peaking for a match.

Coaches, trainers, and sports doctors encourage sprinters in training cessation for objective and subjective monitoring of the degree of fatigue and to avoid the risk of injuries.

To date, the usefulness of measuring muscle stiffness for muscle fatigue has been studied [57]. It has been reported that muscle stiffness increases by performing fatigue tasks [58]. In recent years, new technologies have made it possible to measure muscles stiffness [59]. It may be an effective means for objective assessment of the daily, weekly, and seasonal muscle condition of a sprinter (**Table 5**).

Furthermore, hamstring injury programs should include high-intensity aerobic exercises during the basic training period [60] as previous papers demonstrated the presence of strength-endurance deficits by these injuries [61]. The overall improvement in fitness levels minimizes the fatigue burden [54].

Regardless of the training efficacy, the presence of risk factors makes the program unacceptable. Therefore, monitoring is necessary to ensure the efficacy of provided training without spikes in training load or any risks for hamstring injuries [54].

7. Implications and future directions

The more sprint performance improves, the higher the incidence of hamstring injuries [16, 26], and it is still higher in elite sprinters. A hamstring prevention program is possible by building a support system for program methods (contents) with techniques and strategies based on data accumulation and cooperation of coaches, researchers, trainers, and sports doctors (**Figure 9**).

Future research should verify the effectiveness of this preventive program for hamstring injuries in sprinters. In addition, for more effective prevention, nonmodifiable factors such as anterior pelvic tilt, fiber-type distribution, and previous injury [62] may have been taken into consideration during program execution [6].

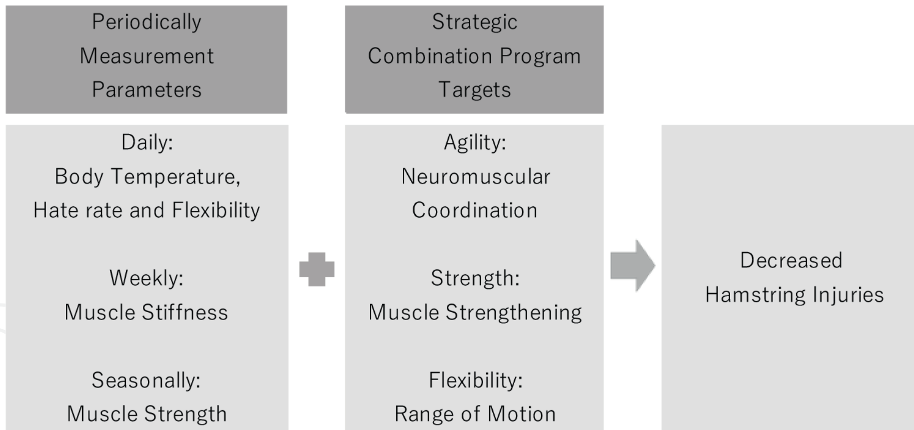

Figure 9.
Ideal hamstring injury prevention program for sprinters.

Conflict of interest

The authors declare no conflict of interest.

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References

[1] Mero A, Komi PV. Effects of supramaximal velocity on biomechanical variables in sprinting. Journal of Applied Biomechanics. 1985;**1**:240-252. DOI: 10.1123/ijsb.1.3.240

[2] Ae M, Miyashita K, Yokoi T, Hashihara Y. Mechanical power and work done by the muscle of the lower limb during running at different speeds. Biomechanics X-B 1987, 6. J Biomech Kinetic limitations of maximal sprinting speed. 1983;**16**(79-83):895-899. DOI: 10.1016/0021-9290(83)90048-9

[3] Chapman AE, Caldwell GE. Kinetic limitations of maximal sprinting speed. Journal of Biomechanics. 1983;**16**:79-83

[4] Mann RV. A kinetic analysis of sprinting. Medicine and Science in Sports and Exercise. 1981;**13**(5):325-328. DOI: 10.1249/00005768-198105000-00010

[5] Dalton SL, Kerr ZY, Dompier TP. Epidemiology of hamstring strains in 25 NCAA sports in the 20092010 to 20132014 academic years. The American Journal of Sports Medicine. 2015;**43**(11):2671-2679. DOI: 10.1177/0363546515599631

[6] Sugiura Y, Sakuma K, Sakuraba K, Sato Y. Prevention of hamstring injuries in collegiate sprinters. Orthopaedic Journal of Sports Medicine. 2017;**5**(1):2325967116681524. DOI: 10.1177/2325967116681524

[7] Brukner P, Khan K. Clinical Sports Medicine. 3rd ed. New Zealand, Australia: McGraw-Hill Medical; 2009

[8] Van der Made AD, Wieldraaijer T, Kerkhoffs GM, Kleipool RP, Engebretsen L, van Dijk CN, et al. The hamstring muscle complex. Knee Surgery, Sports Traumatology, Arthroscopy. 2015;**23**(7):2115-2122. DOI: 10.1007/s00167-013-2744-0

[9] Woodley SJ, Storey RN. Review of hamstring anatomy. Aspetar Sports Medicine Journal. 2013;**2**:432-437

[10] Burkett LN. Investigation into hamstring strains: The case of the hybrid muscle. The Journal of Sports Medicine. 1975;**3**(5):228-231. DOI: 10.1177/036354657500300504

[11] Clanton TO, Coupe KJ. Hamstring Straing in athletes; diagnosis and treatment. The Journal of the American Academy of Orthopaedic Surgeons. 1998;**6**(4):237-248. DOI: 10.5435/00124635-199807000-00005

[12] Pollock N, Kelly S, Lee J, Stone B, Giakoumis M, Polglass G, et al. A 4-year study of hamstring injury outcomes in elite track and field using the British athletics rehabilitation approach. British Journal of Sports Medicine. 2022;**56**(5):257-263. DOI: 10.1136/bjsports-2020-103791

[13] Pollock N, James SLJ, Lee JC, Chakraverty R. British athletics muscle injury classification: A new grading system. British Journal of Sports Medicine. 2014;**48**(18):1347-1351. DOI: 10.1136/bjsports-2013-093302

[14] Simonsen EB, Thomsen L, Klausen K. Activity of mono-and biarticular leg muscles during sprint running. European Journal of Applied Physiology and Occupational Physiology. 1985;**54**(5):524-532. DOI: 10.1007/BF00422964

[15] Stanton P. Hamstring injuries and eccentric exercise. EXCEL. 1986;**3**:13-15

[16] Stanton P, Purdham C. Hamstring injuries in sprinting—The role of eccentric exercise. The Journal of Orthopaedic and Sports Physical Therapy. 1989;**10**(9):343-349. DOI: 10.2519/jospt.1989.10.9.343

[17] Jonkers I, Stewart C, Spaepen A. The complementary role of the plantarflexors, hamstrings and gluteus maximus in the control of stance limb stability during gait. Gait & Posture. 2003;**17**(3):264-272. DOI: 10.1016/s0966-6362(02)00102-9

[18] Schache AG, Dorn TW, Blanch PD, Brown NA, Pandy MG. Mechanics of the human hamstring muscles during sprinting. Medicine and Science in Sports and Exercise. 2012;**44**(4):647-658. DOI: 10.1249/MSS.0b013e318236a3d2

[19] Sugiura Y, Sakuma K, Fujita S, Aoki K, Takazawa Y. Effects of various numbers of runs on the success of hamstring injury prevention program in sprinters. International Journal of Environmental Research and Public Health. 2022;**19**(15):9373. DOI: 10.3390/ijerph19159375

[20] Howard RM, Conway R, Harrison AJ. Muscle activity in sprinting: A review. Sports Biomechanics. 2018;**17**(1):1-17. DOI: 10.1080/14763141.2016.1252790

[21] Orchard J. Biomechanics of muscle strain injury. N Z J Sports Med. 2002;**30**:92-98

[22] Clanton TO, Coupe KJ. Hamsting strains in athletes: Diagnosis and treatment. The Journal of the American Academy of Orthopaedic Surgeons. 1998;**6**(4):237-248. DOI: 10.5435/00124635-199807000-00005

[23] Alonso J, McHugh MP, Mullaney MJ, Tyler TF. Effect of hamstring flexibility on isometric knee flexion angle-torque relationship. Scandinavian Journal of Medicine & Science in Sports. 2009;**19**(2):252-256. DOI: 10.1111/j.1600-0838.2008.00792.x

[24] Mann R, Sprague P. A kinetic analysis of the ground leg during sprint running. Research Quarterly for Exercise and Sport. 1980;**51**(2):334-348. DOI: 10.1080/02701367.1980.10605202

[25] Sugiura Y, Sakuma K, Fujita S, Sakuraba K. Hamstring injury prevention program and recommendation for stride frequency during tow-training optimization. Applied Sciences. 2021;**11**(14):6500. DOI: 10.3390/app11146500

[26] Jönhagen S, Németh G, Eriksson E. Hamstring injuries in sprinters. The role of concentric and eccentric hamstring muscle strength and flexibility. The American Journal of Sports Medicine. 1994;**22**(2):262-266. DOI: 10.1177/036354659402200218

[27] Lysholm J, Wiklander J. Injuries in runners. The American Journal of Sports Medicine. 1987;**15**(2):168-171. DOI: 10.1177/036354658701500213

[28] Chumanov ES, Heiderscheit BC, Thelen DG. Hamstring musculotendon dynamics during stance and swing phases of high-speed running. Medicine and Science in Sports and Exercise. 2011;**43**(3):525-532. DOI: 10.1249/MSS.0b013e3181f23fe8

[29] Fiorentino NM, Rehorn MR, Chumanov ES, Thelen DG, Blemker SS. Computational models predict larger muscle tissue strains at faster sprinting speeds. Medicine and Science in Sports and Exercise. 2014;**46**(4):776-786. DOI: 10.1249/MSS.0000000000000172

[30] Heiderscheit BC, Hoerth DM, Chumanov ES, Swanson SC, Thelen BJ,

Thelen DG. Identifying the time of occurrence of a hamstring strain injury during treadmill running: A case study. Clinical Biomechanics (Bristol Avon). 2005;**20**(10):1072-1078. DOI: 10.1016/j.clinbiomech.2005.07.005

[31] Higashihara A, Nagano Y, Ono T, Fukubayashi T. Relationship between the peak time of hamstring stretch and activation during sprinting. European Journal of Sport Science. 2016;**16**(1):36-41. DOI: 10.1080/17461391.2014.973913

[32] Schache AG, Wrigley TV, Baker R, Pandy MG. Biomechanical response to hamstring muscle strain injury. Gait & Posture. 2009;**29**(2):332-338. DOI: 10.1016/j.gaitpost.2008.10.054

[33] Agre JC. Hamstring injuries. Proposed aetiological factors, prevention, and treatment. Sports Medicine. 1985;**2**(1):21-33. DOI: 10.2165/00007256-198502010-00003

[34] Worrell TW. Factors associated with hamstring injuries: An approach to treatment and preventative measures. Sports Medicine. 1994;**17**(5):338-345. DOI: 10.2165/00007256-199417050-00006

[35] Devlin L. Recurrent posterior thigh symptoms detrimental to performance in rugby union: Predisposing factors. Sports Medicine. 2000;**29**(4):273-287. DOI: 10.2165/00007256-200029040-00005

[36] Proske U, Morgan DL, Brockett CL, Percival P. Identifying athletes at risk of hamstring strains and how to protect them. Clinical and Experimental Pharmacology & Physiology. 2004;**31**(8):546-550. DOI: 10.1111/j.1440-1681.2004.04028.x

[37] Sugiura Y, Saito T, Sakuraba K, Sakuma K, Suzuki E. Strength deficits identified with concentric action of the hip extensors and eccentric action of the hamstrings predispose to hamstring injuryin elite sprinters. The Journal of Orthopaedic and Sports Physical Therapy. 2008;**38**(8):457-464. DOI: 10.2519/jospt.2008.2575

[38] Brockett CL, Morgan DL, Proske U. Human hamstring muscles adapt to eccentric exercise by changing optimum length. Medicine and Science in Sports and Exercise. 2001;**33**(5):783-790. DOI: 10.1097/00005768-200105000-00017

[39] Ekstrand J, Gillquist J. Soccer injuries and their mechanisms: A prospective study. Medicine and Science in Sports and Exercise. 1983;**15**(3):267-270. DOI: 10.1249/00005768-198315030-00014

[40] Askling CM, Tengvar M, Thorstensson A. Acute hamstring injuries in Swedish elite football: Aprospective randomised controlled clinical trial comparing two rehabilitation protocols. British Journal of Sports Medicine. 2013;**47**(15):953-959. DOI: 10.1136/bjsports-2013-092165

[41] Heiderscheit BC, Sherry MA, Silder A, Chumanov ES, Thelen DG. Hamstring strain injuries: Recommendations for diagnosis, rehabilitation, and injury prevention. The Journal of Orthopaedic and Sports Physical Therapy. 2010;**40**(2):67-81. DOI: 10.2519/jospt.2010.3047

[42] Arnason A, Andersen TE, Holme I, Engebretsen L, Bahr R. Prevention of hamstring strains in elite soccer: An intervention study. Scandinavian Journal of Medicine & Science in Sports. 2008;**18**(1):40-48. DOI: 10.1111/j.1600-0838.2006.00634.x

[43] Mjølsnes R, Arnason A, Østhagen T, Raastad T, Bahr RAA. A

10-week randomized trial comparing eccentric vs. concentric hamstring strength training in well-trained soccer players. Scandinavian Journal of Medicine & Science in Sports. 2004;**14**(5):311-317. DOI: 10.1046/j.1600-0838.2003.367.x

[44] Joyce D, Lewindon D. Retraining the injured athlete. In: Joyce D, Lewindon D, editors. High-Performance Training for Sports. Champaign, IL: Human Kinetics Publishers; 2014. pp. 85-96

[45] Sugiura Y, Aoki J. Effects of supramaximal running on stride frequency and stride length in sprinters. Advances in Exercise and Sports Physiology. 2008;**14**:9-17

[46] Ae M, Itoh N, Muraki Y, Miyashita K. Optimal tension of isotonic towing for sprint training. In: Proceedings of the XV Congress of International Society of Biomechanics. Jyvaskyla, Finland; 1995

[47] Ito N. Effects of towing system used a pulley on sprinting. Sprint Res. 1998;**8**:29-37 (In Japanese)

[48] Sugiura Y, Migita T, Sakuraba K, Sakuma K, Aoki J. Effects of tow training on delayed-onset muscle soreness and serum CK activity for sprinters who are accustomed to supramaximal running. Jpn J Clin Sports Med. 2009;**17**:247-254 (In Japanese)

[49] Mero A, Komi PV. Force-, EMG-, and elasticity-velocity relationships at submaximal, maximal and supramaximal running speeds in sprinters. European Journal of Applied Physiology and Occupational Physiology. 1986;**55**(5):553-561. DOI: 10.1007/BF00421652

[50] Dintiman GB. Training the sprinter. In: Cooper JM, editor. What Research Tells the Coach about Sprinting. Reston, VA: AAHPER Publications; 1974. pp. 49-81

[51] Hicks D. Resisted and assisted sprint training: Determining the transfer to maximal sprinting. New Studies In Athletics. 2018;**32**:35-51

[52] Mero A, Komi PV, Rusko H, Hirvonen J. Neuromuscular and anaerobic performance of sprinters at maximal and supramaximal speed. International Journal of Sports Medicine. 1987;**8**(Suppl. 1):55-60. DOI: 10.1055/s-2008-1025704

[53] Huygaerts S, Cos F, Cohen DD, Calleja-González J, Guitart M, Blazevich AJ, et al. Mechanisms of hamstring strain injury: Interactions between fatigue, muscle Activationand function. Sports. 2020;**8**(5):65. DOI: 10.3390/sports8050065

[54] Wing C, Bishop C. Hamstring strain injuries: Incidence, mechanisms, risk factors, and training recommendations. Strength & Conditioning Journal. 2020;**42**(3):40-57. DOI: 10.1519/SSC.0000000000000538

[55] Papadopoulos GST, Siatras T, Kellis S. The effect of static and dynamic stretching exercises on the maximal isokinetic strength of the knee extensors and flexors. Isokinetics and Exercise Science. 2005;**13**(4):285-291. DOI: 10.3233/IES-2005-0216

[56] Rosenblett B. Planning a performance programme. In: Joyce D, Lewindon D, editors. High-Performance Training for Sports. Champaign, IL: Human Kinetics Publishers; 2014. p. 247

[57] Witte RS, Kim K, Martin BJ, O'Donnell M. Effect of fatigue on muscle elasticity in the human forearm using ultrasound strain imaging. In: Conf Proc IEEE Eng Med Biol Soc. Proceedings of

the Annu Int Conf IEEE Eng Med Biol Soc Annu Conf. Piscataway, NJ: IEEE Service Center; 2006. pp. 4490-4493. DOI: 10.1109/IEMBS.2006.260850

[58] Bouillard K, Jubeau M, Nordez A, Hug F. Effect of vastus lateral is fatigue on load sharing between quadriceps femoris muscles during isometric knee extensions. Journal of Neurophysiology. 2014;**111**(4):768-776

[59] Miyamoto N, Hirata K, Inoue K, Hashimoto T. Muscle stiffness of the vastus lateralis in sprinters and long-distance runners. Medicine and Science in Sports and Exercise. 2019;**51**(10):2080-2087. DOI: 10.1249/MSS.0000000000002024

[60] Baker D. Recent trends in high-intensity aerobic training for field sports. Proof Strength Cond. 2011;**22**:38

[61] Lord C, Ma'ayah F, AJAJ B. Change in knee flexor torque after fatiguing exercise identifies previous hamstring injury in football players. Scandinavian Journal of Medicine & Science in Sports. 2018;**28**(3):1235-1243. DOI: 10.1111/sms.13007

[62] Opar DA, Williams MD, Shield AJ. Hamstring strain injuries: Factors that lead to injury and re-injury. Sports Medicine. 2012;**42**(3):209-226. DOI: 10.2165/11594800-000000000-00000