*International Journal of Sports Physiology and Performance*, 2024, 19, 729-737
https://doi.org/10.1123/ijspp.2024-0049


Human Kinetics
BRIEF REVIEW

# Hamstring Injuries, From the Clinic to the Field: A Narrative Review Discussing Exercise Transfer

**Jordi Vicens-Bordas,[1] Ali Parvaneh Sarand,[2] Marco Beato,[3] and Robert Buhmann[4]**

[1]Sport Performance Analysis Research Group (SPARG) and Sport and Physical Activity Studies Center (CEEAF), University of Vic–Central University of Catalonia, Vic, Spain; [2]Department of Physical Education and Sport Sciences, University of Guilan, Rasht, Iran; [3]School of Health and Sports Sciences, University of Suffolk, Ipswich, United Kingdom; [4]School of Health and Behavioral Sciences, University of the Sunshine Coast, Sippy Downs, QLD, Australia

***Purpose****:* The optimal approach to hamstring training is heavily debated. Eccentric exercises reduce injury risk; however, it is argued that these exercises transfer poorly to improved hamstring function during sprinting. Some argue that other exercises, such as isometric exercises, result in better transfer to running gait and should be used when training to improve performance and reduce injury risk. Given the performance requirements of the hamstrings during the terminal swing phase, where they are exposed to high strain, exercises should aim to improve the torque production during this phase. This should improve the hamstrings' ability to resist overlengthening consequently, improving performance and limiting strain injury. Most hamstring training studies fail to assess running kinematics postintervention. Of the limited evidence available, only eccentric exercises demonstrate changes in swing-phase kinematics following training. Studies of other exercise modalities investigate effects on markers of performance and injury risk but do not investigate changes in running kinematics. ***Conclusions****:* Despite being inconsistent with principles of transfer, current evidence suggests that eccentric exercises result in transfer to swing-phase kinematics. Other exercise modalities may be effective, but the effect of these exercises on running kinematics is unknown.

***Keywords****:* rehabilitation, strength, eccentric training, sprinting

Current hamstring training approaches emphasize eccentric exercises (eg, Askling L-protocol and the Nordic hamstring curl).[1–3] Eccentric hamstring exercises are used on the basis that they increase fascicle length and eccentric knee flexor strength.[4,5] Adaptations from eccentric training shift the hamstring torque–joint angle relationship to longer muscle lengths, improving their ability to resist overlengthening during the swing phase of gait.[6] While the benefits of eccentric exercise for hamstring injury rehabilitation are well researched, there is debate whether adaptations from eccentric training transfer to improved running gait performance (improved swing phase mechanics/greater eccentric knee flexor moment) and reduce hamstring strain injury risk.[7–9] In fact, some studies report no association between eccentric knee flexor strength and hamstring strain injury risk.[10,11]

The Nordic hamstring curl is a common strength exercise,[12–14] and programs using this exercise are related to reductions in injury rates.[1] The use of this exercise during hamstring injury rehabilitation is also encouraged in rehabilitation guidelines[15] including rehabilitation principles used by British Athletics.[16] However, some performance staff question the "functionality" of this exercise (ie, it may not mimic the contraction velocity, contraction mode, and hip/knee actions observed during sprinting).[8,17] There are suggestions that the action of the hamstrings during the swing phase of sprinting is quasi-isometric instead of eccentric.[9] This has resulted in the recommendation of training the hamstring muscle group isometrically.[9]

Noting functionality as a barrier to uptake of eccentric exercises such as the Nordic hamstring curl, other modes of exercise have been popularized. For example, high-intensity isometric exercises at optimum muscle lengths involving appropriate patterns of intermuscular coordination (co-activation of hamstring and gluteal muscles) have been proposed as a more functional alternative to eccentric exercises.[9] Van Hooren and Bosch[9] argue the hamstrings act quasi-isometrically during gait, and eccentric exercises may have limited transfer (although further research is needed to verify such claims). Progressive agility and trunk stabilization (PATS) is another proposed approach to training.[18,19] This approach emphasizes pelvic control, limiting unintended increases in hamstring muscle tendon unit length (due to increases in anterior pelvic tilt) during sprinting. Despite the suggestion that these approaches improve hamstring function during running gait, there are limited studies investigating changes in running kinetics/kinematics following these programs.

In rehabilitation, it is important to determine whether training exercises improve the hamstrings' ability to generate torque at long muscle lengths during swing, given the impact this may have on performance and injury risk. There is limited evidence discussing exercises that result in optimum transfer to running gait performance (ie, whether exercises improve eccentric knee flexor torque during swing). Understanding the influence different exercises have on hamstring function during gait will help inform exercise selection. Therefore, this narrative review aims to provide practitioners with a better understanding of contemporary hamstring strain injury rehabilitation by discussing exercises that improve eccentric knee flexor torque production during the swing phase of sprinting.

## Hamstring Demands During Acceleration and High-Speed Running

Before determining which rehabilitation exercises result in optimum transfer to running gait (improved knee flexor torque

Vicens-Bordas https://orcid.org/0000-0002-8388-8863
Sarand https://orcid.org/0000-0002-9126-4217
Beato https://orcid.org/0000-0001-5373-2211
Buhmann (rbuhmann@usc.edu.au) is corresponding author, https://orcid.org/0000-0002-7984-4446

production during swing), it is important to understand the demands of the hamstring muscle group during running. Hamstring injury occurs during acceleration and high-speed running, and these phases impose different demands on the hamstring muscle group (due to differences in stride length/frequency and duration of flight/braking phases).[20] Regardless of the running phase, the hamstrings produce high amounts of eccentric torque and are susceptible to injury during the swing phase,[21–23] the stance phase,[24] and the transition between these phases.[25]

During acceleration, the horizontal component of ground reaction force is maximized, helping propel the center of mass forward.[22] Large hip extensor torques are generated during acceleration, and based on its geometry, the biceps femoris long head is the primary hip extensor.[26] This muscle also demonstrates the greatest amount of electromyographic activity during acceleration compared with other hamstring muscles, with peak activity occurring during the late swing phase.[22] During high-speed running, the hamstrings actively lengthen to decelerate the forward swinging femur and tibia.[23] Similar to acceleration, hamstring force production and electromyographic activity peak during the swing phase[22]; however, the medial hamstring muscles (semitendinosus and semimembranosus) exhibit higher relative levels of electromyographic activity compared with the biceps femoris during the midswing phase.[22] The total length change and elongation velocity are greater during top speed running compared with acceleration, suggesting top speed running imposes greater strain on the hamstring muscle group than acceleration.[27] The biceps femoris long head reaches its peak strain slightly earlier in the gait cycle than other hamstring muscles and consequently operates on the descending limb of its force–length relationship during the late terminal swing phase of gait, possibly increasing risk of strain injury in this muscle.[26] The stance phase also exposes the hamstring muscles to high amounts of stress. The ground reaction force occurring during early stance generates large knee extension and hip flexion torques.[25] This results in lengthening of the hamstrings, and large forces must be applied to counteract this ground reaction force, potentially increasing injury risk during this phase of gait.[25]

To optimize training and rehabilitation, it is also important to understand whether hamstring injury affects hamstring running kinematics. Compared with controls, athletes with an injury history demonstrate increased anterior pelvic tilt, greater hip flexion, and greater thoracic lateral flexion.[28,29] These changes in kinematics, which occur during the late swing phase of the gait cycle in previously injured athletes,[28,29] place the hamstrings in a longer position during running, increasing the imposed strain. These differences in kinematics could signify an inability to resist overlengthening during swing, which is supported by deficits in biceps femoris electromyographic activity.[28] Additionally, lower levels of horizontal force production during sprinting are related to future risk of hamstring strain injury.[30] The hamstrings play a major role in horizontal force production during sprinting with biceps femoris electromyographic activity during swing and eccentric knee flexor peak torque related to horizontal force production.[31] Deficits in hamstring torque production during swing may result in running kinematics that impose greater strain on the muscle and lower levels of horizontal force production. Therefore, to minimize injury risk, it is important that hamstring exercises stimulate increases in eccentric knee flexor torque during the swing phase to limit changes in swing phase kinematics[28,29] and deficits in horizontal force production.

## Current Approach to Hamstring Exercise Selection

Typically, hamstring training programs include range of motion, progressive running, strengthening, and sport-specific components.[3] Many athletes exhibit an eccentric strength deficit,[32] greater neural inhibition,[33–35] and decreased biceps femoris long head activation during late swing phase at high speeds[27] following a hamstring strain injury. As a result, the strengthening component of rehabilitation plays a key role during the return to play phase of the rehabilitation continuum.

There are several approaches to hamstring injury prevention discussed in the literature.[2,3,9,36,37] Among common hamstring training approaches, the Nordic hamstring curl is the most researched hamstring exercise[12–14,38–41] and its use is supported by hamstring rehabilitation guidelines.[15,16] Many studies report reductions in injury risk following Nordic hamstring training, with a relative risk of 0.59 (95% CI, 0.27–1.29) reported by meta-analysis of randomized controlled trials.[42] Initial Nordic hamstring curl training studies describe a 10-week program progressing from 2 sets of 5 repetitions once per week to 3 sets of 8 to 12 repetitions 3 times per week,[43] although beneficial adaptations can occur with shorter training periods (2 sets of 4 repetitions, once per week).[40] The Nordic hamstring curl potentially reduces injury risk by increasing eccentric knee flexor strength and biceps femoris long head fascicle length,[44] which improves the ability of the muscle to resist overlengthening during the swing phase of gait.[13]

Other exercises, despite having a sound theoretical basis, have not been included in prospective training studies and/or randomized controlled trials. Cross-sectional studies have examined patterns of hamstring activity during the stiff leg deadlift,[38] 45° hip extension,[45] supine bridge,[46] and flywheel leg curl.[47] The aim of these investigations is to determine which exercises optimally activate the biceps femoris long head—the most frequently injured hamstring muscle.[32] Many of these investigations suggest hip-based movements preferentially recruit the biceps femoris long head,[48] and these exercises should be used during rehabilitation. However, more recent evidence reports greater relative levels of biceps femoris activity during the Nordic hamstring curl compared with other hamstring muscles,[38] particularly at knee angles closer to full extension.[49] Additionally, there is between-participant variability in the hamstring muscle most heavily recruited during the Nordic hamstring curl and stiff leg deadlift exercises, but those favoring a specific hamstring muscle during a particular exercise also favor this muscle during other exercises.[38] In vivo investigations report estimated peak muscle force produced by the biceps femoris is greater during the Nordic hamstring curl compared with other common hamstring exercises.[50]

Given the potential for hamstring injury during eccentric actions (late swing and early stance), there has been a focus on accentuated eccentric training when training the hamstrings.[51–53] It is suggested this mode of training results in superior adaptations compared with conventional resistance training.[53,54] Flywheel training—where athletes create inertial torque by pulling a cable attached to a flywheel during the concentric phase of the exercise, which they must resist as it pulls against them during the eccentric portion of the movement[55,56]—is a popular mode of loading the eccentric phase of a movement. Typically, these machines have many attachments, meaning users can perform many conventional resistance training exercises (eg, stiff leg deadlift and leg curl) with accentuated eccentric load.[57,58] Training with the stiff leg deadlift on a flywheel device increases eccentric strength and lengthens biceps femoris long head fascicles,[59] and the degree of change is similar to Nordic curl training.[57] This mode of training also has a positive uptake from practitioners with many reporting a perceived "functional" benefit and a reduced likelihood of future noncontact muscular injury.[52,60]

The Askling L-protocol (the extender, diver, and glider exercises) is another highly cited training program.[61] This program involves eccentric exercises and, compared with programs including concentric-eccentric exercises, results in a shorter return to play time and fewer reinjuries at follow-up.[61] Despite the L-protocol aiming to reduce injury incidence and risk through similar mechanisms as the Nordic hamstring curl, these exercises lack the appropriate overload to stimulate fascicle length increases.[2] When overload (extra weight 5–20 kg) is added to these exercises, increases in eccentric strength and biceps femoris fascicle length are reported.[62] Therefore, although lower injury incidence is observed in participants following training using the L-protocol, it is difficult to determine whether these exercises have the same efficacy as the Nordic hamstring curl, given studies typically only use bodyweight as the load.

Despite the benefits of eccentric hamstring training, Van Hooren and Bosch[9] argue there is no transfer to running due to differences in contraction velocity, range of motion, and intermuscular coordination between the 2 exercise modes. Additionally, some propose a quasi-isometric contraction of the hamstrings during swing[9] and suggest eccentric exercises are ineffective when aiming to improve hamstring function during running gait. Proponents of isometric training suggest that exercises should mimic the action and intermuscular coordination of the hamstrings during running.[9] Hamstring exercises incorporating multiple joints where the aim is to resist hip flexion while emphasizing control of the pelvis (eg, single-leg roman chair hold and split squat with forward lean) have been recommended.[9] The rationale behind these types of exercises is to teach appropriate pelvic control, consequently limiting unintended pelvic tilt.[9] A similar rationale is used to support other hamstring training approaches such as progressive agility and trunk stabilization.[18,19] Such an approach is supported by biomechanical modeling, which demonstrates an increase in hamstring strain with increases in anterior pelvic tilt.[21] While the theoretical basis for these exercises is sound, there is minimal evidence demonstrating the changes in running performance (and minimization of injury risk) following these training methods. Although one recent study has reported increases in biceps femoris long head fascicle length following isometric knee flexor training.[63]

Training programs should aim to improve running performance and limit injury risk through exercises that increase eccentric knee flexor torque production during the swing phase of gait. It is suggested that sprint training is included in these programs,[7] partly based on higher levels of hamstring surface electromyography observed during sprinting compared with conventional exercises (eg, the Nordic hamstring curl)[64] and the perceived likelihood of transfer to competition. However, contraction speed (which is high during running) influences the electromyographic signal despite no changes in muscle activation and comparison between movements of different speeds are discouraged.[65] Biomechanical modeling studies report similar force production during running and conventional hamstring exercises (peak forces of 23 and 26 N/kg produced by the biceps femoris long head during a stiff leg deadlift and sprinting, respectively).[23,50] Additionally, fascicle length excursions of ~23 mm have been reported during the stiff leg deadlift,[50] a length increase of approximately 20% from the reported resting fascicle length (~10 cm).[5] The peak hamstring muscle strain observed during sprinting (compared with upright posture) is approximately 10%.[23] Therefore, despite the ecological validity of running, it is likely other hamstring exercises expose the muscle group to similar levels of force production and lengthening, and likely result in beneficial transfer (improved eccentric knee flexor moments during swing) and should be considered during training.

Transfer occurs when the training activity represents the untrained action,[66] in this case, improved eccentric knee flexor moments during the late swing phase in sprinting. Representative hamstring exercises would therefore maximize force production of the semitendinosus and biceps femoris while in lengthened positions[67] and involve rapid unilateral eccentric knee flexor contraction while the hip is flexed[23,68] (eg, pulley hip extension exercise[69]). There are many exercises that are inconsistent with the principles of transfer yet demonstrate beneficial adaptations (for performance and injury prevention) and reduce future injury risk. Additionally, there are many exercises employed during rehabilitation that are theoretically sound but have not been investigated in the context of running performance improvement or future hamstring injury risk.[9] To reduce injury risk, athletes must perform exercises that stimulate the necessary adaptations in the hamstring muscle group that allow them to counteract the high levels of stress and strain occurring during running gait. It is essential to understand which groups of exercises result in these adaptations (regardless of whether they are consistent with transfer principles) to best prepare athletes for return to competition.

## Do Commonly Used Rehab Exercises Transfer to Improved Running-Gait Performance?

Although inconsistent with principles of transfer, training with exercises like the Nordic hamstring curl results in adaptations that are beneficial for running performance and reduce injury risk.[13,14,40,70] Most studies report an improvement in (ie, faster) sprint time over short distances (5–30 m)[14,39,41] and increases (approx. 10%–15%) in eccentric hamstring strength following short-term (4–6 wk) training.[12,41] One study reports small increases in sprint times (ie, slower times) following Nordic training.[71] Additionally, despite the relatively slow contraction velocity during the Nordic hamstring curl, studies report increases in eccentric strength when assessed during fast contractions on an isokinetic dynamometer.[13,41] For example, one study controlled the contraction velocity during Nordic training ($15°\cdot s^{-1}$) and reported increases in eccentric strength (+ 12%) during knee flexor contractions on a dynamometer at $150°\cdot s^{-1}$ following training.[12] This suggests training-induced eccentric strength gains may transfer to different contraction velocities. Only one study has investigated the transfer of Nordic hamstring curl training to swing phase mechanics during sprinting.[13] Following training, increases in eccentric hamstring moment recorded during Nordics were related to increased knee ($R^2 = .83$) and hip ($R^2 = .72$) joint moments during the terminal swing phase of gait.[13] This demonstrates that adaptations occurring as a result of training using the Nordic hamstring curl have a positive transfer on swing phase kinematics, which likely improves the hamstrings' ability to produce torque at long muscle lengths.[23] Van Hooren et al[50] also report the largest excursions in fascicle length during the Nordic (compared with other hamstring exercises), suggesting it is most suited for stimulating increases in fascicle length. Overall, training studies using the Nordic hamstring curl demonstrate improvements in running performance,[12,14,39] adaptations associated with reduced injury risk,[40,70] and improvements in hamstring function during the swing phase of gait.[13]

In contrast to the Nordic hamstring curl, flywheel training is more consistent with principles of transfer. Flywheel devices are also effective for applying eccentric overload during exercises in lengthened positions—where the hamstrings are likely to sustain injury during sprinting (see Suarez-Arrones et al[69] for an example exercise). Like the Nordic, flywheel resistance training emphasizes the eccentric contraction. Additionally, the contraction velocity can be increased or decreased depending on the performer's intent, the characteristics of the device used (moment of inertia and shaft type—cylinder or cone), and the type of exercise selected. Therefore, flywheel training can be considered an adaptable resistance modality to obtain hamstring adaptations (both neural and morphological).[72] Training studies involving flywheel training report increases in braking and propulsive forces during a change of direction task,[73] faster change of direction performance,[74] and faster 40 m sprint times.[75] Lower hamstring injury rates have been reported in football players performing flywheel training compared with controls in a single small-scale study (n = 30)[76]; however, no studies to date have investigated the biomechanical mechanisms behind these findings. Although promising, more studies are needed to determine the effect of this training mode on injury incidence and hamstring function during sprinting.

In addition to eccentric training, the effect of lumbopelvic training on sprinting kinematics has been investigated.[77] Lumbopelvic training involves employing a multimodal intervention to improve an athlete's ability to minimize disruptions to pelvic position during running gait. Recently, it has been shown that this type of training results in reduced anterior pelvic tilt by ~5° during swing, reduced hip extension of the rear thigh during toe off, and less hip flexion during swing.[77] These changes in kinematics theoretically reduce the strain imposed upon the hamstrings during running. Although this study[77] did not report changes to knee moments following the training intervention, the observed changes in pelvic position would result in smaller hamstring length changes during sprinting, imposing less strain upon the muscle group. While this training approach can result in changes in running performance, there are no randomized controlled trials demonstrating improvements in lumbopelvic control result in reduced risk of future injury.

## Can We Improve Transfer From Rehabilitation to Running Gait?

To improve performance and reduce the risk of hamstring injury during sprinting, rehabilitation exercises should aim to improve the eccentric knee flexor torque production during terminal swing.[23] Improving this capacity will allow hamstring muscle fibers to resist overlengthening and limit the risk of strain injury.[6] Therefore, to improve the transfer of hamstring rehabilitation exercises to running, it is necessary to understand which exercises result in this adaptation. Eccentric exercises have shown some merit in this capacity, but other exercises also have theoretical merit (although lack supporting evidence from randomized controlled trials). For example, "catch" exercises (see Krommes et al[78] for an example) involving rapid hamstring force production while lengthening and overcoming inertia are consistent with principles of transfer and may stimulate improved eccentric hamstring moments while running (although the effect of training with these exercises on running kinematics has not been studied). Additionally, the "catch" can be applied to several commonly used rehabilitation exercises (eg, a prone leg curl, a stiff leg deadlift where the weight is "dropped" and quickly "caught" by the performer). While these exercises possess theoretical merit, cross-sectional studies demonstrate that although a hamstring "catch" exercise results in greater angular velocity at the knee, the rate of rise of electromyographic activity is slower when compared with a Nordic hamstring curl.[78] This suggests that while the "catch" exercise was designed to stimulate rapid activation of the hamstrings, the Nordic hamstring curl (a comparatively slower exercise) results in a faster rate of development of electromyographic activity. This is an important consideration as the rate of muscle recruitment during training may stimulate adaptations that allow muscles to better resist deformation during a stretch shorten cycle (eg, increased stiffness).[79,80] Researchers should be cautious when making inferences regarding the degree of muscle activation when assessed with electromyography,[81,82] but this study is the only current evidence available providing any indication whether these types of exercises are effective for improving hamstring function during running gait. Employing these types of exercises in an acute rehabilitation setting may also be risky as it is difficult to control weight/tension and force production (abrupt changes in force production in long positions may aggravate injury).

Sprint training—typically involving periodized running drills, with volume progressively increased over time—is also used to prepare and rehabilitate the hamstrings.[70,71] The main supporting argument for this mode of training is that it closely mimics the intensity and frequency of actions during a competitive fixture, and that the length/tension demands and high levels of electromyographic activity observed during sprinting will result in optimal architectural adaptations.[71] Sprint training typically results in improvements (faster) in short sprint (5–20 m) times and sprint kinetics.[71] Additionally, sprint training results in lengthening of biceps femoris long head fascicles[71] and increased eccentric knee flexor strength,[70] possibly resulting in reduced injury risk.[44] It is also worth noting that, in one study, sprint training resulted in greater self-reported soreness (compared with the Nordic hamstring curl) within participants[70]—soreness is typically seen as a barrier to uptake for eccentric exercises.[8,17]

Other exercises consistent with the principles of transfer include bounding-type exercises. Again, there is limited evidence for these types of exercises resulting in improved hamstring function during gait. Interestingly, despite their consistency with principles of transfer, "bounding" exercises do not result in a reduction in hamstring injury incidence compared with a control group (who continued to perform regular training).[83] This suggests these types of exercises do not stimulate the muscular adaptations necessary to withstand the high amounts of strain during terminal swing. Although the length and possibly contraction velocities during bounding exercises may better represent sprinting (compared with traditional resistance exercises), peak hamstring muscle force production occurs at speeds >80% of maximum.[21] Therefore, the slower running that occurs during bounding may not produce the necessary hamstring muscle forces to stimulate adaptations that prevent injury. Together, current evidence from studies of exercises consistent with transfer principles (although sparse) suggests that the Nordic hamstring curl, despite being inconsistent with transfer principles, stimulates beneficial adaptations and results in greater protection from injury.[40,57] However, prospective studies are required to understand whether alternative exercises result in beneficial adaptations to running kinematics.

Optimizing transfer from training exercises to running gait may require better understanding and incorporation of different

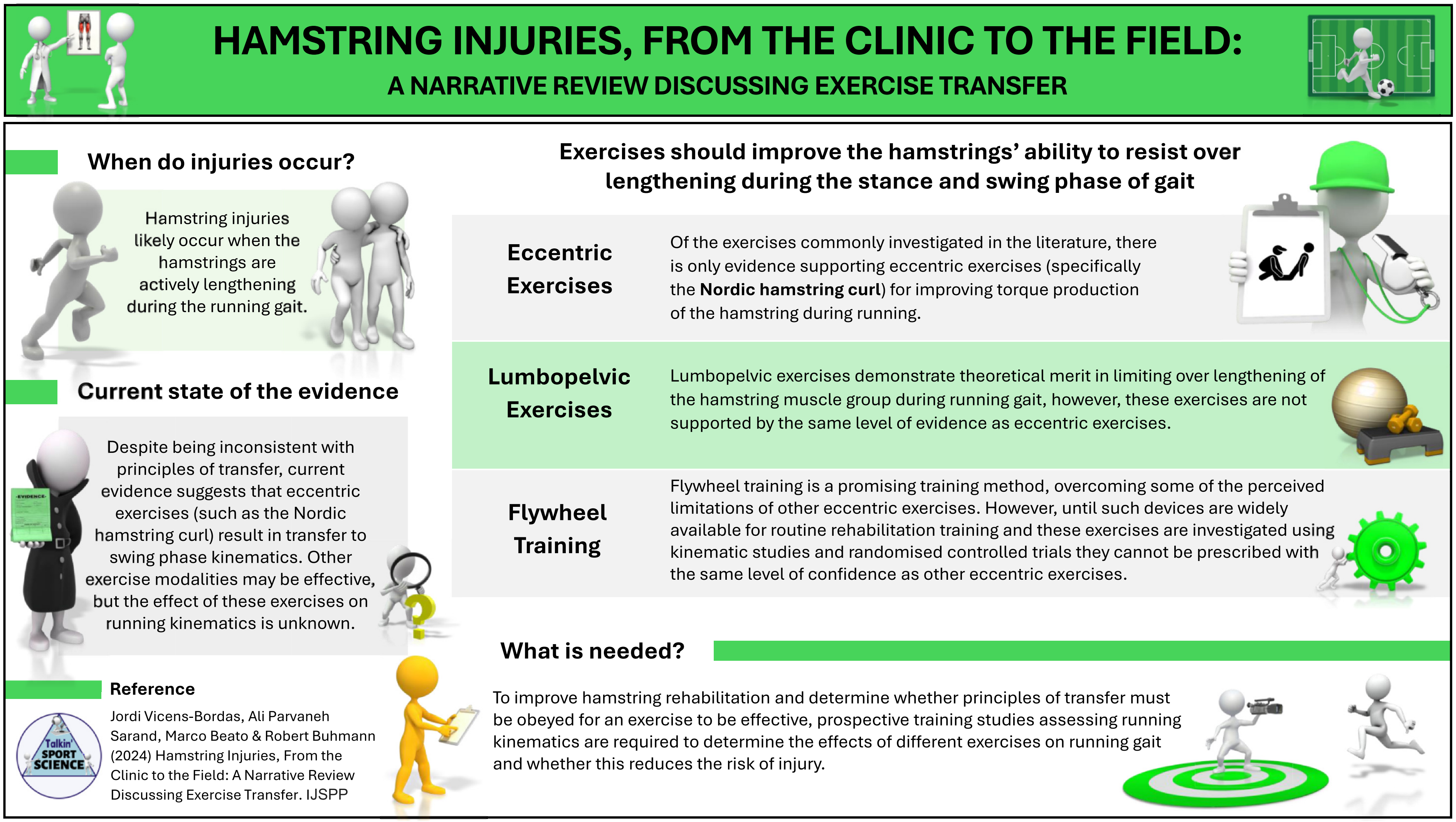


**Figure 1** — Infographic summarizing this paper.

types of running drills and high-speed running programming. For example, studies of hamstring function during running demonstrate that as speed progresses from 80% to 100%, musculotendon length of the biceps femoris long head remains relatively constant, while force production increases linearly (peaking at maximum speed).[21] This finding demonstrates the need for exposure to high-speed running during rehabilitation to prepare athletes for return to competition. A failure to regularly expose athletes to >80% of maximum running speed means the biceps femoris muscle is not trained to withstand high amounts of strain. While there are some recommendations for incorporating running into rehabilitation based on expert opinion,[3] there is a need for prospective studies to determine how to best integrate acceleration and top speed running into rehabilitation within the constraints of pain. Additionally, other rehabilitation guidelines, including when to initiate sprint training (at speeds >80% of maximum), optimal sprint distances, and the rate of progression (eg, speed and distance/volume), also require consideration. Acceleration and top speed running drills (while they should not form the only activity during rehabilitation) are consistent with transfer principles and may help restore/improve hamstring function during the swing phase of gait.

Accounting for individual variability in muscle activity during exercises[38] may also help improve the transfer to running gait. There is individual variation in electrical activity of specific hamstring muscles during the Nordic hamstring curl and stiff leg deadlift.[38] Recent evidence demonstrates the muscle favored during hip and knee movements varies between individuals.[38] Biases toward a particular hamstring muscle persist across different movements (ie, those who favor the recruitment of the biceps femoris during the Nordic also favor its recruitment during a stiff leg deadlift).[38] These biases may limit the efficacy of conventional rehabilitation approaches. For instance, if an injured athlete sustained an injury to the biceps femoris, yet this athlete demonstrated preferential recruitment of the semitendinosus during conventional rehabilitation exercises, the injured biceps femoris may not be appropriately stimulated during rehabilitation and could be susceptible to reinjury. Determining whether individualized rehabilitation (by assessing an athletes' pattern of muscle activity using electromyography) improves postinjury outcomes requires investigation. Such evidence would encourage therapists to prescribe exercises that address the muscle involved in the injury (eg, if the biceps femoris is injured and this muscle displays low levels of activity during conventional exercises, the therapist could investigate alternate exercises that favor recruitment of this muscle). Although this approach may not be suitable for all levels of practice given the cost requirement and user expertise associated with electromyography, there is a need to understand the clinical relevance of individual differences in patterns of hamstring muscle activity during different movements.[38]

## Practical Applications

Exercise selection is an important consideration when preparing the hamstrings for competition, and the practitioner has many options to choose from when programming exercises. As injury likely occurs when the hamstrings are actively lengthening during running gait, exercises should improve the hamstrings' ability to resist overlengthening during the stance and swing phase of gait. Of the exercises commonly investigated in the literature, there is only evidence supporting eccentric exercises (specifically the Nordic hamstring curl) for improving torque production of this muscle group during running gait. Lumbopelvic exercises demonstrate theoretical merit in limiting overlengthening of the hamstring muscle group during running gait; however, these exercises are not supported by the same level of evidence as eccentric exercises. As a result, if the aim of these exercises is to improve the capacity of the hamstring muscle group to produce torque during active lengthening, or limit overlengthening while running, lumbopelvic exercises cannot be prescribed with the same level of confidence as eccentric exercise. Similarly, flywheel training is a promising training method, overcoming some of the perceived limitations of other eccentric exercises.[56] However, until such devices are widely available for routine rehabilitation training and these exercises are investigated using kinematic studies and randomized controlled trials, they cannot be prescribed with the same level of confidence as other eccentric exercises. Overall, eccentric exercises (such as the Nordic hamstring curl) are supported by evidence from prospective studies analyzing running kinematics and can be prescribed with more confidence than other modes of exercise if the goal is to improve the torque-generating capacity of the hamstring muscle group during running gait. Randomized controlled trials are required before other approaches to rehabilitation (eg, isometric exercises[9]) can be prescribed with the same level of confidence. The infographic in Figure 1 summarizes the primary points of this review.

## Conclusions

Although inconsistent with principles of transfer, Nordic hamstring curl training studies demonstrate lower hamstring injury rates in intervention groups compared with control groups. Prospective studies incorporating the Nordic hamstring curl also demonstrate improvements in hamstring strength and field-based performance measures, increases in fascicle length, and associations with beneficial changes in swing phase kinematics, although there is only a small number of these studies. Other modes of training (eg, flywheel training) are more consistent with principles of transfer and warrant investigation. To improve hamstring rehabilitation and determine whether principles of transfer must be obeyed for an exercise to be effective, prospective training studies assessing running kinematics are required to determine the effects of different exercises on running gait and whether this reduces the risk of injury. Until such evidence, and randomized controlled trials investigating the effects of alternate training interventions on injury rates and performance are available, practitioners should prioritize the use of eccentric exercises for hamstring rehabilitation as there is evidence showing these exercises improve performance and reduce injury rates.

### Acknowledgment

The authors of this paper acknowledge Talkin' SPORT SCIENCE for their support in drawing the infographic and designing and recording the summary video for this paper (https://www.youtube.com/watch?v=qYEVIxX8zYE).

## References

1. Al Attar WSA, Soomro N, Sinclair PJ, Pappas E, Sanders RH. Effect of injury prevention programs that include the Nordic hamstring exercise on hamstring injury rates in soccer players: a systematic review and meta-analysis. *Sports Med*. 2017;47(5):907–916. PubMed ID: 27752982 doi:10.1007/s40279-016-0638-2

2. Alonso-Fernandez D, Martinez-Fernandez J, Docampo-Blanco P, Fernandez-Rodriguez R. Impact of askling L-PROTOCOL on biceps femoris architecture, hamstring flexibility and sprint performance. *Int J Sports Med*. 2022;43(4):373–380. PubMed ID: 34464983 doi:10.1055/a-1627-0957
3. Hickey JT, Opar DA, Weiss LJ, Heiderscheit BC. Current clinical concepts: hamstring strain injury rehabilitation. *J Athl Train*. 2021; 57:125–135. doi:10.4085/1062-6050-0707.20
4. Duhig SJ, Bourne MN, Buhmann RL, et al. Effect of concentric and eccentric hamstring training on sprint recovery, strength and muscle architecture in inexperienced athletes. *J Sci Med Sport*. 2019; 22(7):769–774. PubMed ID: 30772189 doi:10.1016/j.jsams.2019.01.010
5. Pincheira PA, Boswell MA, Franchi MV, Delp SL, Lichtwark GA. Biceps femoris long head sarcomere and fascicle length adaptations after 3 weeks of eccentric exercise training. *J Sport Health Sci*. 2022; 11(1):43–49. PubMed ID: 34509714 doi:10.1016/j.jshs.2021.09.002
6. Brockett CL, Morgan DL, Proske U. Predicting hamstring strain injury in elite athletes. *Med Sci Sports Exerc*. 2004;36(3):379–387. PubMed ID: 15076778 doi:10.1249/01.MSS.0000117165.75832.05
7. Beato M, Drust B, Iacono AD. Implementing high-speed running and sprinting training in professional soccer. *Int J Sports Med*. 2021; 42(4):295–299. PubMed ID: 33291180 doi:10.1055/a-1302-7968
8. Chesterton P, Tears C. The uptake of the Nordic hamstring exercise programme as an injury prevention strategy in professional cricket in the United Kingdom and barriers to implementation. *Phys Ther Sport*. 2021;50:1–6. PubMed ID: 33839376 doi:10.1016/j.ptsp.2021.03.013
9. Van Hooren B, Bosch F. Is there really an eccentric action of the hamstrings during the swing phase of high-speed running? part II: implications for exercise. *J Sports Sci*. 2017;35(23):2322–2333. PubMed ID: 27935419 doi:10.1080/02640414.2016.1266019
10. Dyk N van, Bahr R, Burnett AF, et al. A comprehensive strength testing protocol offers no clinical value in predicting risk of hamstring injury: a prospective cohort study of 413 professional football players. *Br J Sports Med*. 2017;51(23):1695–1702. PubMed ID: 28756392 doi:10.1136/bjsports-2017-097754
11. Roe M, Delahunt E, McHugh M, et al. Association between eccentric knee flexor strength and hamstring injury risk in 185 elite gaelic football players. *Scand J Med Sci Sports*. 2020;30(3):515–522. PubMed ID: 31663638 doi:10.1111/sms.13588
12. Alt T, Nodler YT, Severin J, Knicker AJ, Strüder HK. Velocity-specific and time-dependent adaptations following a standardized Nordic hamstring exercise training. *Scand J Med Sci Sports*. 2018; 28(1):65–76. PubMed ID: 28247444 doi:10.1111/sms.12868
13. Alt T, Severin J, Komnik I, et al. Nordic Hamstring Exercise training induces improved lower-limb swing phase mechanics and sustained strength preservation in sprinters. *Scand J Med Sci Sports*. 2021; 31(4):826–838. PubMed ID: 33341995 doi:10.1111/sms.13909
14. Krommes K, Petersen J, Nielsen MB, Aagaard P, Hölmich P, Thorborg K. Sprint and jump performance in elite male soccer players following a 10-week nordic hamstring exercise protocol: a randomised pilot study. *BMC Res Notes*. 2017;10(1):669. doi:10.1186/s13104-017-2986-x
15. Schmitt B, Tim T, McHugh M. Hamstring injury rehabilitation and prevention of reinjury using lengthened state eccentric training: a new concept. *Int J Sports Phys Ther*. 2012;7(3):333–341. PubMed ID: 22666648
16. Macdonald B, McAleer S, Kelly S, Chakraverty R, Johnston M, Pollock N. Hamstring rehabilitation in elite track and field athletes: applying the British athletics muscle injury classification in clinical practice. *Br J Sports Med*. 2019;53(23):1464–1473. PubMed ID: 31300391 doi:10.1136/bjsports-2017-098971
17. Chesterton P, Draper G, Portas M, Tears C. The uptake of Nordic hamstring exercise program for injury prevention in major league soccer and its barriers to implementation in practice. *J Sport Rehabil*. 2022;31:576–581. PubMed ID: 35272267 doi:10.1123/jsr.2021-0262
18. Sherry MA, Best TM. A comparison of 2 rehabilitation programs in the treatment of acute hamstring strains. *Res Rep*. 2004;34(3): 116–125.
19. Silder A, Sherry MA, Sanfilippo J, Tuite MJ, Hetzel SJ, Heiderscheit BC. Clinical and morphological changes following 2 rehabilitation programs for acute hamstring strain injuries: a randomized clinical trial. *J Orthop Sports Phys Ther*. 2013;43(5):284–299. PubMed ID: 23485730 doi:10.2519/jospt.2013.4452
20. Mero A, Komi PV, Gregor RJ. Biomechanics of sprint running: a review. *Sports Med*. 1992;13(6):376–392. PubMed ID: 1615256 doi:10.2165/00007256-199213060-00002
21. Chumanov ES, Heiderscheit BC, Thelen DG. The effect of speed and influence of individual muscles on hamstring mechanics during the swing phase of sprinting. *J Biomech*. 2007;40(16):3555–3562. PubMed ID: 17659291 doi:10.1016/j.jbiomech.2007.05.026
22. Higashihara A, Nagano Y, Ono T, Fukubayashi T. Differences in hamstring activation characteristics between the acceleration and maximum-speed phases of sprinting. *J Sports Sci*. 2018;36(12): 1313–1318. PubMed ID: 28873030 doi:10.1080/02640414.2017.1375548
23. Schache AG, Dorn TW, Blanch PD, Brown NAT, Pandy MG. Mechanics of the human hamstring muscles during sprinting. *Med Sci Sports Exerc*. 2012;44(4):647–658. PubMed ID: 21912301 doi:10.1249/MSS.0b013e318236a3d2
24. Kenneally-Dabrowski CJB, Brown NAT, Lai AKM, Perriman D, Spratford W, Serpell BG. Late swing or early stance? A narrative review of hamstring injury mechanisms during high-speed running. *Scand J Med Sci Sports*. 2019;29(8):1083–1091. PubMed ID: 31033024 doi:10.1111/sms.13437
25. Liu Y, Sun Y, Zhu W, Yu J. The late swing and early stance of sprinting are most hazardous for hamstring injuries. *J Sport Health Sci*. 2017;6(2):133–136. PubMed ID: 30356597 doi:10.1016/j.jshs.2017.01.011
26. Kellis E, Blazevich AJ. Hamstrings force–length relationships and their implications for angle-specific joint torques: a narrative review. *BMC Sports Sci Med Rehabil*. 2022;14(1):166. doi:10.1186/s13102-022-00555-6
27. Higashihara A, Ono T, Tokutake G, et al. Hamstring muscles' function deficit during overground sprinting in track and field athletes with a history of strain injury. *J Sports Sci*. 2019;37(23): 2744–2750. PubMed ID: 31608831 doi:10.1080/02640414.2019.1664030
28. Daly C, McCarthy Persson U, Twycross-Lewis R, Woledge RC, Morrissey D. The biomechanics of running in athletes with previous hamstring injury: a case–control study. *Scand J Med Sci Sports*. 2016; 26(4):413–420. PubMed ID: 25913546 doi:10.1111/sms.12464
29. Schuermans J, Van Tiggelen D, Palmans T, Danneels L, Witvrouw E. Deviating running kinematics and hamstring injury susceptibility in male soccer players: cause or consequence? *Gait Posture*. 2017; 57:270–277. PubMed ID: 28683419 doi:10.1016/j.gaitpost.2017.06.268
30. Edouard P, Lahti J, Nagahara R, et al. Low horizontal force production capacity during sprinting as a potential risk factor of hamstring injury in football. *Int J Environ Res Public Health*. 2021;18(15):7827. doi:10.3390/ijerph18157827
31. Morin JB, Gimenez P, Edouard P, et al. Sprint acceleration mechanics: the major role of hamstrings in horizontal force production. *Front*

*Physiol*. 2015;6:404. https://www.frontiersin.org/articles/10.3389/fphys.2015.00404
32. Opar DA, Williams MD, Shield AJ. Hamstring strain injuries: factors that lead to injury and re-injury. *Sports Med*. 2012;42(3): 209–226. PubMed ID: 22239734 doi:10.2165/11594800-000000000-00000
33. Buhmann R, Siqueira Trajano G, Kerr G, Shield A. Voluntary activation and reflex responses after hamstring strain injury. *Med Sci Sports Exerc*. 2020;52(9):1862–1869. PubMed ID: 32102061
34. Buhmann R, Trajano GS, Kerr GK, Shield AJ. Increased short interval intracortical inhibition in participants with previous hamstring strain injury. *Eur J Appl Physiol*. 2022;122(2):357–369. PubMed ID: 34729636 doi:10.1007/s00421-021-04839-6
35. Buhmann R, Trajano GS, Kerr GK, Shield AJ. Lower knee flexion and hip extension rate of torque development in athletes with previous hamstring strain injury. *J Sports Sci*. 2022;40(5):534–541. PubMed ID: 34787048 doi:10.1080/02640414.2021.2003981
36. Erickson LN, Sherry MA. Rehabilitation and return to sport after hamstring strain injury. *J Sport Health Sci*. 2017;6(3):262–270. PubMed ID: 30356646 doi:10.1016/j.jshs.2017.04.001
37. Guex K, Millet GP. Conceptual framework for strengthening exercises to prevent hamstring strains. *Sports Med*. 2013;43(12):1207–1215. PubMed ID: 24062275 doi:10.1007/s40279-013-0097-y
38. Boyer A, Hug F, Avrillon S, Lacourpaille L. Individual differences in the distribution of activation among the hamstring muscle heads during stiff-leg deadlift and Nordic hamstring exercises. *J Sports Sci*. 2021;39(16):1830–1837. PubMed ID: 33678131 doi:10.1080/02640414.2021.1899405
39. Ishøi L, Hölmich P, Aagaard P, Thorborg K, Bandholm T, Serner A. Effects of the Nordic hamstring exercise on sprint capacity in male football players: a randomized controlled trial. *J Sports Sci*. 2018; 36(14):1663–1672. PubMed ID: 29192837 doi:10.1080/02640414.2017.1409609
40. Presland JD, Timmins RG, Bourne MN, Williams MD, Opar DA. The effect of Nordic hamstring exercise training volume on biceps femoris long head architectural adaptation. *Scand J Med Sci Sports*. 2018; 28(7):1775–1783. PubMed ID: 29572976 doi:10.1111/sms.13085
41. Siddle J, Greig M, Weaver K, Page RM, Harper D, Brogden CM. Acute adaptations and subsequent preservation of strength and speed measures following a Nordic hamstring curl intervention: a randomised controlled trial. *J Sports Sci*. 2019;37(8):911–920. PubMed ID: 30369285 doi:10.1080/02640414.2018.1535786
42. Impellizzeri FM, McCall A, Meyer T. Registered reports coming soon: our contribution to better science in football research. *Sci Med Footb*. 2019;3(2):87–88. doi:10.1080/24733938.2019.1603659
43. Mjølsnes R, Arnason A, Østhagen T, Raastad T, Bahr RA. 10-Week randomized trial comparing eccentric vs. concentric hamstring strength training in well-trained soccer players. *Scand J Med Sci Sports*. 2004;14(5):311–317. PubMed ID: 15387805 doi:10.1046/j.1600-0838.2003.367.x
44. Timmins RG, Bourne MN, Shield AJ, Williams MD, Lorenzen C, Opar DA. Short biceps femoris fascicles and eccentric knee flexor weakness increase the risk of hamstring injury in elite football (soccer): a prospective cohort study. *Br J Sports Med*. 2016;50(24): 1524–1535. PubMed ID: 26675089 doi:10.1136/bjsports-2015-095362
45. Bourne MN, Williams MD, Opar DA, Najjar AA, Kerr GK, Shield AJ. Impact of exercise selection on hamstring muscle activation. *Br J Sports Med*. 2017;51(13):1021–1028. PubMed ID: 27467123 doi:10.1136/bjsports-2015-095739
46. Bourne M, Williams M, Pizzari T, Shield A. A functional MRI exploration of hamstring activation during the supine bridge exercise. *Int J Sports Med*. 2018;39(2):104–109. PubMed ID: 29161747 doi:10.1055/s-0043-121150
47. Fernandez-Gonzalo R, Tesch PA, Linnehan RM, et al. Individual muscle use in hamstring exercises by soccer players assessed using functional MRI. *Int J Sports Med*. 2016;37:559–564. PubMed ID: 27116347 doi:10.1055/s-0042-100290
48. Bourne MN, Timmins RG, Opar DA, et al. An evidence-based framework for strengthening exercises to prevent hamstring injury. *Sports Med*. 2018;48(2):251–267. PubMed ID: 29116573 doi:10.1007/s40279-017-0796-x
49. Hirose N, Tsuruike M, Higashihara A. Biceps femoris muscle is activated by performing nordic hamstring exercise at a shallow knee flexion angle. *J Sports Sci Med*. 2021;20(2):275. doi:10.52082/jssm.2021.275
50. Van Hooren B, Vanwanseele B, van Rossom S, et al. Muscle forces and fascicle behavior during three hamstring exercises. *Scand J Med Sci Sports*. 2022;32(6):997–1012. PubMed ID: 35307884 doi:10.1111/sms.14158
51. Brughelli M, Cronin J. Altering the length-tension relationship with eccentric exercise: implications for performance and injury. *Sports Med Auckl NZ*. 2007;37(9):807–826. doi:10.2165/00007256-2007 37090-00004
52. de Keijzer KL, Raya-González J, López Samanés Á, Moreno Perez V, Beato M. Perception and use of flywheel resistance training amongst therapists in sport. *Front Sports Act Living*. 2023;5:1141431. https://www.frontiersin.org/articles/10.3389/fspor.2023.1141431
53. Wagle JP, Taber CB, Cunanan AJ, et al. Accentuated eccentric loading for training and performance: a review. *Sports Med*. 2017;47(12): 2473–2495. PubMed ID: 28681170 doi:10.1007/s40279-017-0755-6
54. Munger CN, Archer DC, Leyva WD, et al. Acute effects of eccentric overload on concentric front squat performance. *J Strength Cond Res*. 2017;31(5):1192–1197. PubMed ID: 28151781 doi:10.1519/JSC.0000000000001825
55. Allen WJC, De Keijzer KL, Raya-González J, Castillo D, Coratella G, Beato M. Chronic effects of flywheel training on physical capacities in soccer players: a systematic review. *Res Sports Med*. 2023;31(3):228–248. PubMed ID: 34315310 doi:10.1080/15438627.2021.1958813
56. Beato M, de Keijzer KL, Muñoz-Lopez A, et al. Current guidelines for the implementation of flywheel resistance training technology in sports: a consensus statement. *Sports Med*. 2024;54(3):541–556. PubMed ID: 38175461 doi:10.1007/s40279-023-01979-x
57. Timmins RG, Filopoulos D, Nguyen V, et al. Sprinting, strength, and architectural adaptations following hamstring training in australian footballers. *Scand J Med Sci Sports*. 2021;31(6):1276–1289. PubMed ID: 33617061 doi:10.1111/sms.13941
58. Tous-Fajardo J, Maldonado RA, Quintana JM, Pozzo M, Tesch PA. The flywheel leg-curl machine: offering eccentric overload for hamstring development. *Int J Sports Physiol Perform*. 2006;1(3):293–298. PubMed ID: 19116442 doi:10.1123/ijspp.1.3.293
59. Beato M, de Keijzer KL, Fleming A, et al. Post flywheel squat vs. flywheel deadlift potentiation of lower limb isokinetic peak torques in male athletes. *Sports Biomech*. 2023;22(11):1514–1527. PubMed ID: 33112722 doi:10.1080/14763141.2020.1810750
60. Keijzer K de, McErlain-Naylor SA, Brownlee TE, Raya-González J, Beato M. Perception and application of flywheel training by professional soccer practitioners. *Biol Sport*. 2021;39(4):809–817. PubMed ID: 36247955 doi:10.5114/biolsport.2022.109457
61. Askling CM, Tengvar M, Tarassova O, Thorstensson A. Acute hamstring injuries in swedish elite sprinters and jumpers: a prospective randomised controlled clinical trial comparing two rehabilitation protocols. *Br J Sports Med*. 2014;48(7):532–539. PubMed ID: 24620041 doi:10.1136/bjsports-2013-093214

62. Marušič J, Vatovec R, Marković G, Šarabon N. Effects of eccentric training at long-muscle length on architectural and functional characteristics of the hamstrings. *Scand J Med Sci Sports*. 2020;30(11): 2130–2142. PubMed ID: 32706442 doi:10.1111/sms.13770
63. Timmins RG, Filopoulos D, Giannakis J, et al. The effect of eccentric or isometric training on strength, architecture, and sprinting across an australian football season. *Med Sci Sports Exerc*. 2024;56(3):564–574. PubMed ID: 38051129 doi:10.1249/mss.0000000000003326
64. van den Tillaar R, Solheim JAB, Bencke J. Comparison of hamstring muscle activation during high-speed running and various strengthening exercises. *Int J Sports Phys Ther*. 2017;12(5):718–727. PubMed ID: 29181249
65. Vigotsky AD, Halperin I, Lehman GJ, Trajano GS, Vieira TM. Interpreting signal amplitudes in surface electromyography studies in sport and rehabilitation sciences. *Front Physiol*. 2018;8:985. https://www.frontiersin.org/articles/10.3389/fphys.2017.00985
66. Issurin VB. Training transfer: scientific background and insights for practical application. *Sports Med*. 2013;43(8):675–694. PubMed ID: 23633165 doi:10.1007/s40279-013-0049-6
67. Ono T, Higashihara A, Shinohara J, Hirose N, Fukubayashi T. Estimation of tensile force in the hamstring muscles during overground sprinting. *Int J Sports Med*. 2015;36(2):163–168. PubMed ID: 25254895 doi:10.1055/s-0034-1385865
68. Yu B, Queen RM, Abbey AN, Liu Y, Moorman CT, Garrett WE. Hamstring muscle kinematics and activation during overground sprinting. *J Biomech*. 2008;41(15):3121–3126. PubMed ID: 18848700 doi:10.1016/j.jbiomech.2008.09.005
69. Suarez-Arrones L, Núñez FJ, Lara-Lopez P, Salvo VD, Méndez-Villanueva A. Inertial flywheel knee- and hip-dominant hamstring strength exercises in professional soccer players: muscle use and velocity-based (mechanical) eccentric overload. *PLoS One*. 2020; 15(10):e0239977. doi:10.1371/journal.pone.0239977
70. Freeman B, Young W, Smyth A, Talpey S, Pane C, Carlon T. The effects of sprint training and the Nordic hamstring exercise on eccentric hamstring strength and sprint performance in adolescent athletes. *J Sports Med Phys Fitness*. 2018;59:1119–1125. doi:10.23736/S0022-4707.18.08703-0
71. Mendiguchia J, Conceição F, Edouard P, et al. Sprint versus isolated eccentric training: comparative effects on hamstring architecture and performance in soccer players. *PLoS One*. 2020;15(2):e0228283. doi: 10.1371/journal.pone.0228283
72. Beato M, Dello Iacono A. Implementing flywheel (Isoinertial) exercise in strength training: current evidence, practical recommendations, and future directions. *Front Physiol*. 2020;11:569. https://www.frontiersin.org/articles/10.3389/fphys.2020.00569
73. de Hoyo M, Sañudo B, Carrasco L, et al. Effects of 10-week eccentric overload training on kinetic parameters during change of direction in football players. *J Sports Sci*. 2016;34(14):1380–1387. PubMed ID: 26963941 doi:10.1080/02640414.2016.1157624
74. Raya-González J, Castillo D, de Keijzer KL, Beato M. The effect of a weekly flywheel resistance training session on elite U-16 soccer players' physical performance during the competitive season. A randomized controlled trial. *Res Sports Med*. 2021;29(6):571–585. PubMed ID: 33401975 doi:10.1080/15438627.2020.1870978
75. Suarez-Arrones L, Villarreal ES de, Núñez FJ, et al. In-season eccentric-overload training in elite soccer players: effects on body composition, strength and sprint performance. *PLoS One*. 2018; 13(10):e0205332. doi:10.1371/journal.pone.0205332
76. Askling C, Karlsson J, Thorstensson A. Hamstring injury occurrence in elite soccer players after preseason strength training with eccentric overload. *Scand J Med Sci Sports*. 2003;13(4):244–250. PubMed ID: 12859607 doi:10.1034/j.1600-0838.2003.00312.x
77. Mendiguchia J, Castaño-Zambudio A, Jiménez-Reyes P, et al. Can we modify maximal speed running posture? Implications for performance and hamstring injury management. *Int J Sports Physiol Perform*. 2022;17(3):374–383. PubMed ID: 34794121 doi:10.1123/ijspp.2021-0107
78. Krommes K, Jakobsen MD, Bandholm T, et al. Cross-sectional study of EMG and EMG rise during fast and slow hamstring exercises. *Int J Sports Phys Ther*. 16(4):1033–1042. doi:10.26603/001c.25364
79. Kubo K, Ishigaki T, Ikebukuro T. Effects of plyometric and isometric training on muscle and tendon stiffness in vivo. *Physiol Rep*. 2017; 5(15):e13374. doi:10.14814/phy2.13374
80. Secomb JL, Farley OR, Nimphius S, Lundgren L, Tran TT, Sheppard JM. The training-specific adaptations resulting from resistance training, gymnastics and plyometric training, and non-training in adolescent athletes. *Int J Sports Sci Coach*. 2017;12(6):762–773. doi: 10.1177/1747954117727810
81. Vigotsky AD, Halperin I, Trajano GS, Vieira TM. Longing for a longitudinal proxy: acutely measured surface EMG amplitude is not a validated predictor of muscle hypertrophy. *Sports Med*. 2022;52(2): 193–199. PubMed ID: 35006527 doi:10.1007/s40279-021-01619-2
82. Vigotsky AD, Ogborn D, Phillips SM. Motor unit recruitment cannot be inferred from surface EMG amplitude and basic reporting standards must be adhered to. *Eur J Appl Physiol*. 2016;116(3):657–658. PubMed ID: 26705245 doi:10.1007/s00421-015-3314-6
83. van de Hoef PA, Brink MS, Huisstede BMA, et al. Does a bounding exercise program prevent hamstring injuries in adult male soccer players? A cluster-RCT. *Scand J Med Sci Sports*. 2019;29(4):515–523. PubMed ID: 30536639 doi:10.1111/sms.13353