Hamstring Strains: Basic Science and Clinical Research Applications for Preventing the Recurrent Injury

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SUMMARY

HAMSTRING INJURIES OCCUR FREQUENTLY, WITH A HIGH RECURRENCE RATE, IN SPORTS THAT REQUIRE EITHER HIGH-SPEED SKILLED MOVEMENTS OR EXCESSIVE HIP FLEXION WITH KNEE EXTENSION. A PREVIOUS HAMSTRING INJURY IS THE GREATEST RISK FACTOR FOR A FUTURE HAMSTRING INJURY, WHICH HAS LED SPORTS MEDICINE PROFESSIONALS TO SEARCH FOR IMPROVED POSTINJURY REHABILITATION STRATEGIES. ATHLETES MAY SHOW POSTINJURY STRUCTURAL CHANGES IN THE MUSCLE-TENDON UNIT AND BE AT RISK FOR REINJURY FOR UP TO A YEAR AFTER RETURN TO SPORT. UNDERSTANDING THE POSTINJURY CHANGES CAN HELP CREATE PRACTICAL APPLICATIONS FOR APPROPRIATE RECONDITIONING AND SPORTS PERFORMANCE PROGRAMS.

PURPOSE

This article attempts to demonstrate the size and scope of the acute hamstring injury by describing its incidence in various sports and the difficulty in return to those sports without impaired performance and a high risk of reinjury. It will also help the reader understand what happens anatomically and physiologically after an acute hamstring injury. This understanding is the prerequisite to the ultimate purpose, which is to provide practical applications for the sports medicine and performance team that help return athletes to sport with reduced risk for recurrent injury.

INTRODUCTION

Acute hamstring strain injuries are common in sports that involve sprinting, kicking, or high-speed skilled movements (2,4,10,15,21,23,33,34,38, 41,52,60–62). A retrospective review of the National Collegiate Athletic Association Injury Surveillance System found that male college athletes were 62% more likely to sustain a hamstring injury than female athletes and more common in field sports than in court sports (19). A National Football League team published injury data, including preseason training camp from 1998 to 2007, and found that hamstring strains were the second most common injury, only surpassed by knee sprains (23). Injury rates varied by position, with it being the highest percentage of total injuries among running backs (22%), defensive backs (14%), and wide receivers (12%) (23). A 4-year study of injury rates within a Division 1 football team showed that hamstring strains were the third most common orthopedic problem, behind

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knee and ankle injuries (15). A 2-year analysis of professional soccer teams revealed that 12% of all injuries were hamstring strains (61). In addition to high-speed sports, there is an increased risk for hamstring strains in sports involving slow extreme stretching-type maneuvers, such as dancing (3,4).

Hamstring strain injuries often result in significant recovery time and have a lengthy period of increased susceptibility for recurrent injury (36,46,47). Reinjury rates reported in the literature vary depending on the population, the interventions used, and the duration of follow-up. A study that analyzed 858 hamstring strains in Australian footballers showed that the rate of recurrence was 12.6% during the first week of return to sports and 8.1% for the second week. The cumulative risk of reinjury for the entire 22-week season was 30.6% (46). Another study reported the recurrence rate at 1 year to be as low as 7.7% (52), but most often, recurrence rates are near 30% or higher (10,38,52).

RISK FACTORS FOR HAMSTRING INJURY

The high incidence of injury and frustration associated with trying to return to sport without reinjury have led several researchers to search for risk factors that predispose athletes to hamstring injury. If these risk factors were identifiable, they could then potentially be addressed and modified through injury prevention programs. To date, there is some evidence to suggest previous hamstring injury, older age (relative for competitive athletes), decreased quadriceps flexibility, and muscle imbalances of the thigh are risk factors for hamstring injury.

Gabbe et al. (24) showed that decreased quadriceps flexibility, as assessed by the modified Thomas test, was an independent risk factor for hamstring strains in community-level Australian rules football players. However, measurements, such as hamstring flexibility when measured with the sit and reach test, passive straight leg raise, and the active knee extension test, have not been related to a higher incidence of hamstring strain injury (24,26,27). One study found that hamstring-to-quadriceps strength imbalances can be a risk factor for reinjury (18). It is important to note that 31% of the individuals with a recurrent hamstring injury in that study displayed normal hamstring strength, suggesting that strength imbalances alone cannot explain the risk for reinjury after a hamstring strain. Older age, relative for competitive athletes, has also been identified as a risk factor for hamstring injury in several studies (24,26,33). A recent prospective study evaluated 508 soccer players in an attempt to determine if player position, age, previous hamstring injury, subjective rating, or physical performance capabilities could determine risk for hamstring injury (22). The physical performance tests included a Nordic hamstring strength test, 40-m sprint test, and countermovement jump test. Their results suggest that previous acute hamstring injury was the only significant risk factor for a new hamstring injury. Specifically, the previously injured players were more than twice as likely to sustain a new hamstring injury as their noninjured counterparts. Other studies have also found that a previous hamstring injury is a significant risk factor for recurrent injury, suggesting that postinjury changes to the muscle and altered movement patterns may persist that contribute to this increased risk (6,22,24,33,38,47).

MECHANISM OF HAMSTRING INJURY

Most hamstring strain injuries happen while running. It is generally believed that they occur during terminal swing phase of the gait cycle (29,45). This is supported by the objective findings from 2 separate hamstring injury case studies (50). During the second half of the swing, the hamstrings undergo an eccentric contraction and absorb energy from the swing limb before foot contact (16,63). Thus, the hamstrings are stretched while subjected to load (eccentric contraction), with the biceps femoris incurring the greatest amount of length change and performing the greatest amount of negative work during this time (58,59). This may contribute to the tendency of the biceps femoris to be more often injured than the semimembranosus and semitendinosus (5).

ANATOMY AND PHYSIOLOGY OF HAMSTRING INJURY

Most hamstring injuries occur along the proximal musculotendon junction (MTJ) (20), where the muscle fibrils intersect with the tendon (30). Like most acute strain injuries, hamstring strains do not typically involve the muscle tearing away from the tendon. In fact, it is the muscle tissue adjacent to the MTJ that is damaged (31). Immediately after injury, there is an acute inflammatory response that is followed by muscle and collagen regeneration (8). An injury such as this can result in fibrous scar formation. Structural changes within the muscle immediately after an acute hamstring strain injury have been investigated (17,32,39,40). The amount and extent of edema and hemorrhage on magnetic resonance (MR) images can confirm the presence and severity of initial muscle fiber damage and can also provide a reasonable estimate of the rehabilitation period, especially in the moderate and severe cases (17,32,56). MR imaging and clinical assessment with regard to the less severe acute hamstring strains may not necessarily be definitive (51). For example, in 18 of the 58 cases studied, a clinical diagnosis of hamstring injury was made with no positive identification of injury on MR images (51). It is unknown whether MR is not sensitive enough to identify more mild strains or if other injuries may clinically mimic mild hamstring strains.

Animal models of muscle injury have shown that the growth of fibrous tissue prevails over muscle regeneration and eventually leads to the presence of mature acellular scarring at the site of injury (37,44). For example, imaging studies in humans have found evidence of scar tissue as soon as 6 weeks after injury (17). Animal models suggest that scar tissue may persist indefinitely

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Table 1
Dynamic warm-up drills

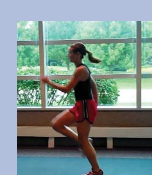
A march	1. Move arms in opposition of the legs	 
	2. Drive 1 knee up to waist height, at the top of the knee lift the foot should be parallel with the ground. At that point, the opposite arm should be forward with hand open	
	3. Then, drive that leg toward the ground contacting the ball of the foot while driving the opposite knee up toward waist height	
	4. Repeat this cycle	
A skips	1. Drive 1 knee up to waist height, at the top of the knee lift the foot should be parallel with the ground. At the same time, the opposite leg should be creating a powerful push off leading to a hop	   
	2. After that leg hops, then the other leg steps forward in preparation for its hop. Then, drive that opposite knee up to waist height. Always contact the ground first with the ball of the foot, not the heel	
	3. Repeating this cycle, the pattern is step-hop, step-hop, etc.	

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Table 1
(continued)

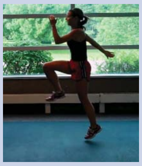
B skips	1. Drive 1 knee up to waist height, at the top of the knee lift the foot should be parallel with the ground. At the same time, the opposite leg should be creating a powerful push off leading to a hop	   
	2. After that leg hops, then the other leg steps forward in preparation for its hop. Then, drive that opposite knee up to waist height. Always contact the ground first with the ball of the foot, not the heel	
	3. Just before the descent, the athlete should quickly extend the knee out toward a running stride position	
	4. Repeating this cycle, the pattern is step-hop, step-hop, etc.	
Short stride cariocas	1. Start in an athletic position (hips and knees slightly flexed, weight toward the ball of the feet)	  
	2. Move the trail foot across the lead foot in front of the body. The hips and pelvis should rotate in this direction such that the legs do not actually touch	
	3. Then, move the trail foot across the lead foot behind the body. The hips and pelvis should rotate in this direction such that the legs do not actually touch. When done correctly, the feet maintain a similar distance from each other at all times, and most of the rotation occurs through the pelvis	
	4. The speed and amplitude of arm motion should match that of the legs but be in opposition	

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Table 1
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Side shuffles	1. Start in an athletic position (hips and knees slightly flexed, weight toward the ball of the feet)	 
	2. The trail leg pushes off forcefully enough to create a slight airborne phase that translates the body laterally	
	3. The lead leg accepts the weight transfer and then quickly shifts weight back to the trail leg	
	4. The majority of the effort should be with the hips; thus, the shoulder height and head height will remain consistent. It is also important to keep the feet perpendicular to the path of travel	
Leg cycling and leg pawing	1. Stand on 1 leg	  
	2. At a medium speed, bring the other leg up to a position replicating the end of a running stride	
	3. Then, quickly and powerfully pull the leg back and behind you	
	4. Repeat this cycle continuously on the same leg	
	The leg cycling exercise does not produce any ground contact with the swing leg	
	The pawing exercise creates a forceful contact to the ball of the foot of the swing leg in front of the body	
	This exercise gets its name from the image of a horse pawing the ground	

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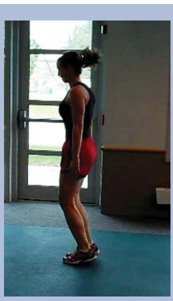
Table 1 (continued)		
Ankle pops	1. Push off the ball of 1 foot quickly and forcefully to create push off at the ankle	 
	2. Land by creating initial contact at the ball of the foot and absorbing the landing force with the ankle quickly enough to repeat the push off in a plyometric fashion	
	3. The knee and hip should be slightly flexed but not significantly involved in the force production or reduction	
	4. This can be done on 2 feet or 1 foot	
Quick support running drills, forward falling running drills, and explosive starts	Quick support running drills involve any quick change in position immediately followed by a sprint (e.g., jump squat-sprint)	  
	Forward falling running drills involve any sequence where the athlete's body is drifting into a positive shin angle or forward lean and then followed by a sprint (e.g., tall-fall-run)	

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Table 1
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	Explosive starts are drills in which the athlete needs to rapidly assume the correct acceleration posture to work to a sprint (e.g., scramble ups)	     

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Table 2
Trunk stabilization and core control exercises

Low to high wood chops	1. The athlete grabs a cable or resistance band with 2 hands at knee height or lower and cable in a position parallel to the frontal plane of the body. Thus, at the start, the athlete will assume rotation toward the trail leg and triple flexion to lower hands to the start point	
	2. From the starting point, the athlete generates rotation force through the hips and core to rotate toward the lead leg while simultaneously moving into extension at the shoulders, hips, knees, and ankles	
	3. At the end of the movement, the athlete will be rotated about 90° relative to the frontal plane with arms overhead	
	4. The athlete then returns to the start position in reverse order	
High to low wood chops	1. The athlete grabs a cable or resistance band with 2 hands at or above head height and cable in a position parallel to the frontal plane of the body. Thus, at the start, the athlete will assume rotation toward the trail leg and triple extension to reach hands to the start point	
	2. From the starting point, the athlete generates rotation force through the hips and core to rotate toward the lead leg while simultaneously moving into flexion at the shoulders, hips, knees, and ankles	
	3. At the end of the movement, the athlete will be rotated about 90° relative to the frontal plane with hands at about knee height	
	4. The athlete then returns to the start position in reverse order	

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Table 2
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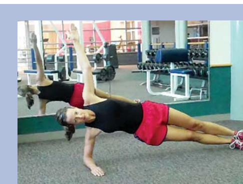
Rotating core planks	1. The athlete lies on his or her side with his or her lower forearm and elbow under his or her shoulder. The legs are on top of each other	
	2. Then, tighten the abdominals to lift your hips	
	3. Lift hips to a height where they create a straight line from shoulder to hip to ankle or just slightly higher. The head should stay in line with your spine. Hold this position for 2 s	
	4. Now rotate the chest toward the floor without dropping the hips	
	5. Place the other forearm on the ground and rotate the body like a pencil such that now the athlete is in the opposite side bridge position	
	6. Continue back and forth in this fashion	
Physioball bridging with alternating leg holds and alternating hip position	1. The athlete lies on his or her back with both heels on the ball	
	2. The athlete bridges up, or lifts hips, off the ground to the desired position. The professional may ask them to bridge all the way up to neutral hip extension or may desire for them to perform in some hip flexion. Either way, the spine should be in neutral	
	3. The angle of knee flexion may also vary upon instruction to work multiple angles of knee flexion and thus hamstring length	
	4. After a brief pause, the athlete switches to the other leg to hold	
	5. This exercise can also be made more difficult by changing the arm position, the closer the arms are to the body and the less of the arms touching the ground, the more challenging it will be	

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Table 2
(continued)

Single-leg stand rotating reaches	1. The athlete starts by standing on one leg and has the other leg slightly behind her	  
	2. Balance on the standing leg without using arms to control body sway. Make sure to keep hip and knee slightly flexed so that the athlete is not "locking out" the standing leg	
	3. Next, the chest moves forward and free leg backward, keeping them in line with each other. The athlete moves as far as they can control with the goal of reaching parallel to the floor. Simultaneously, during the trunk movement, the opposite arm should be reaching down and across the standing leg, this will also induce some thoracic rotation	
	4. Pause at the end of that movement and return to the start position. The athlete should try to initiate the next repetition without touching the other foot to the ground. The athlete should also alternate which arm is reaching. This is a difficult exercise, the goal is to control and minimize hip and knee frontal plane excursion	

(8,39). These changes may increase the stiffness of the MTJ and thereby alter the relative amount of stretch taken up by the adjacent muscle and tendinous tissue (7,49). The long-term effects of a hamstring strain injury have been shown to persist in some people until at least 23 months after injury (53). In this study, 14 subjects had returned to full sporting activity without self-perceived symptoms or performance deficits, yet residual scar tissue was present along the MTJ adjacent to the site of presumed previous injury for 11 of the 14 subjects.

The significance of these persistent musculotendon morphological changes to reinjury risk is not definitively known at the present time. Proske et al. (48) showed that after hamstring injury, the optimum length for active force generation was reduced. This change subsequently causes the angle of peak torque to occur at a greater knee flexion angle (i.e., shorter optimum musculotendon length for active tension) compared with the noninjured side. Proske et al. and Morgan et al. (9,48) then suggested a correlation with the increase in the risk of injury recurrence with the shorter optimum length for tension, as it would create susceptibility to damage from eccentric contractions of the hamstrings occurring in the late swing phase of running. These findings created a speculation that the replacement of muscle with scar tissue after injury was the cause for this. However, a more recent retrospective study of athletes with a history of unilateral hamstring strain injuries found that a consistent shift in the angle of peak torque was not observed (55). The same study investigated the effect of scar tissue on musculotendon dynamics by assessing running kinematics at 4 speeds ranging from 60 to 100% of maximum sprinting speed (55). It was speculated that peak stretch of the hamstring muscles might be reduced in the previously injured limb compared with the contralateral side as a compensation for the modified tissue. However, no

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Table 3
Eccentric training exercises

Eccentric box drops	1. Begin by stepping up onto a box (12–36 in.)	
	2. He or she then steps off the box and lands in a squat position	
	3. Allow for significant flexion of the hips, knees, and ankles upon foot contact	
	4. Then, stand up slowly	
Eccentric loaded lunge drops	1. The athlete rises up onto his or her toes while taking a lunge stance, with or without resistance	
	2. He or she then quickly drops onto the ground with his or her feet landing flat and balanced	
	3. Then, he or she will resist the downward forces into a deep lunge position while maintaining good posture. The majority of the athlete's weight should be on the lead leg	

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Table 3
(continued)

Eccentric forward pulls	1. The athlete starts in a partial squat position with arms out in front of the chest holding a rope or cable	 
	2. While maintaining this position throughout the exercise, he or she slowly pulls the load backward, emphasizing knee extension in a hip flexed position	
	3. On the return phase, the athlete contacts the lead leg near full extension (with hips flexed) and controls knee flexion	
Split-stance Zerchers	1. The athlete starts by holding the medicine ball (or other weight) in front of the body at chest height. The athlete should stand with one leg in front of the other, with most of the body weight on the forward leg. The knee should be almost straight but not hyperextended	 
	2. The athlete then flexes forward with all of the motion occurring at the hips while maintaining the same back and knee position	
	3. The athlete stops the forward lean when feeling tension in the hamstring and then uses the hamstrings and gluts to return to the starting position	
Single-leg deadlifts	1. The athlete starts in a single-leg stand position with that knee just slightly flexed. Hold dumbbells in each hand. He or she may also use a medicine ball or bar with both hands	 
	2. The athlete then flexes forward with all of the motion occurring at the hips while maintaining the same knee and back position. The cervical spine should also stay in a neutral position. This will require the opposite leg to rise up and back, maintaining an "in-line" posture with the torso. The cervical spine should stay in neutral	
	3. The athlete stops the forward lean when feeling tension in the hamstring and then uses the hamstrings and glutes to return to the starting position without touching the other leg to the ground	

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significant asymmetries in overall hamstring musculotendon stretch were observed at any of the speeds tested (55). Other studies have also shown similar findings in a group of athletes tested at submaximal sprinting speeds (12,42). It seems that joint-level mechanics or local neuromuscular control patterns do not appear to be consistently altered.

It is possible that scar tissue may alter local contraction mechanics, thereby influencing reinjury risk. To investigate this possibility, CINE phase-contrast MR imaging has been used to measure muscle tissue velocities adjacent to the previous injury in a group of previously injured athletes (55). This type of imaging technique allowed us to measure tissue velocities within the biceps femoris muscle tissue, adjacent to the proximal MTJ. Measurements were taken while the subjects performed cyclic knee flexion-extension for both elastic and inertial loading conditions. The elastic and inertial loads induced active shortening and lengthening contractions, respectively. Muscle tissue velocities obtained during these tasks were integrated to estimate displacements and subsequently used to calculate tissue strain (54). Both healthy and previously injured subjects exhibited increased muscle strains near the proximal MTJ (54). In addition, subjects with previous injury presented with significantly greater muscle tissue strains when compared with their healthy counterparts (54). It therefore seems likely that residual scar tissue at the site of a previous injury may adversely affect local tissue mechanics in a way that could contribute to reinjury risk.

REHABILITATION AND RECONDITIONING

Rehabilitation programs should address components of these basic science findings in addition to clinical findings. In response to eccentric exercise, an increase in serial sarcomeres has been suggested (43). This would allow the muscle-tendon unit to operate at longer lengths and decrease the magnitude of the stretch absorbed by each sarcomere and likely the corresponding strain. Clinical investigations involving eccentric training have also shown benefits in reducing the incidence of hamstring strain injuries. One study showed a decrease in hamstring injury after a program of concentric and eccentric contractions on a YoYo flywheel ergometer (2), whereas 3 other studies have shown a decrease in hamstring injury after eccentric training using the Nordic curl exercise (1,10,25). Despite the benefit of these programs, they can have significantly low compliance rates (21,25). There are also authors who are critical of the training specificity of the Nordic curl, noting that it is a bilateral movement that only generates movement from the knees (11). Thus, despite its demonstrated benefit, there may be potential for even greater benefit using a unilateral eccentric exercise that incorporated hip and knee motion.

Rehabilitation and reconditioning efforts must also appreciate more regional factors influencing function. Musculoskeletal modeling has recently demonstrated the substantial influence that lumbopelvic muscles can have on the overall stretch of the hamstrings (16). For example, contralateral hip flexor (i.e., iliopsoas) activity during high-speed running has a large influence on ipsilateral hamstring stretch. That is because activity of the iliopsoas can produce an increase in anterior pelvic tilt during early swing phase, the stretch of the contralateral hamstrings is increased. A recent experimental study of normal running mechanics has confirmed the bilateral coupling between hip extension and contralateral hamstring stretch (57). This coupling may, in part, explain why rehabilitation exercises targeting neuromuscular control of muscles in the lumbopelvic region are effective at reducing hamstring reinjury rates (52).

This influence of lumbopelvic muscles on hamstring dynamics was prospectively assessed by comparing reinjury rates in athletes with hamstring strains who were treated with a progressive agility and trunk stabilization (PATS) program and those treated with a hamstring strengthening and stretching (SS) program (52). Both programs were to be completed at least 5 times per week. The PATS group had a reinjury rate of 0 and 7.7% at 2 weeks and 1 year after return to sport, respectively, whereas the SS group had a reinjury rate of 54.5 and 70% at 2 weeks and 1 year after return to sport, respectively (52). Although the morphological and neuromuscular factors were not measured, it does suggest that there may be a role of lumbopelvic neuromuscular control in the prevention of future hamstring injury. In fact, Cameron et al. (13) demonstrated that below-average neuromuscular control can predispose athletes to hamstring injury. They prospectively investigated limb neuromuscular control with a leg swing movement discrimination test in a weight-bearing position in 28 Australian Football League players. The movement discrimination test involved backward swinging of the leg to a contact plate without visual reference. The purpose of the test was to assess lower limb neuromuscular control (13). Of those 28 players, 6 subsequently injured their hamstring that season. All 6 players had movement discrimination scores below the mean. This led to the creation of the "HamSprint program" during which a series of drills are conducted to improve running technique, coordination, and hamstring function (14). Some drills in this program included leg cycling, pawing, ankle pops, high knee marching, quick support running drills, forward falling running drills, and explosive starts (Table 1). After 6 weeks of training using the HamSprint program, athletes significantly improved their movement discrimination scores when compared with a control group that performed regular stretching, running, and football drills (14). Based on the findings from these 2 studies, Cameron et al. (14) theorized that the HamSprint program could be an effective hamstring injury prevention

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program. These drills are similar to the drills that Gambetta and Benton (28) have advocated for hamstring injury prevention. They theorized that these drill would improve running mechanics and sport-specific training of the hamstrings. A similar hypothesis was used for soccer athletes. A training program consisting of a variety of single-leg balance, takeoff and landing exercises, that were theorized to improve neuromuscular control for soccer, were studied. A positive effect was seen for this proprioceptive balance training program by an observed decrease in noncontact hamstring injuries in female soccer players (41). At the completion of the 3-year prospective program, noncontact hamstring injury rates were reduced from 22.4 to 8.2/1,000 hours ($p = 0.021$) (41). These studies suggest that proprioceptive and neuromuscular control mechanisms may be affected by injury and just as importantly have an important role in preventing future injury.

PRACTICAL APPLICATIONS

The scientific evidence presented creates a sound basis for the following practical applications. Consistent implementation of these practical applications consistently should improve return to sport after injury by expediting return to optimal athletic function and reducing the chance of recurrent injury.

DYNAMIC WARM-UP

Upon return to sport after injury, athletes should incorporate a dynamic warm-up before practice or competition. The HamSprint program by Cameron et al. (14) demonstrated that dynamic agility drills can improve lower limb motor control and that this has a relationship to hamstring injury. Postinjury research has also shown that the use of progressive agility exercises is an effective way to prevent reinjury (52). Based on these principles, an appropriate dynamic warm-up program should include specific drills shown to improve running technique, lumbopelvic control, and hamstring function. Such drills could include A marching, A skips, B skips, short stride cariocas, side shuffles, leg cycling, leg pawing, ankle pops, quick support running drills, forward falling running drills, and explosive starts (Table 1) (see **Video**, **Supplemental Digital Content 1**, http://links.lww.com/SCJ/A5, labeled "Dynamic Warm-Up Drills").

TRUNK STABILIZATION AND NEUROMUSCULAR CONTROL EXERCISES

Upon return to sport after injury, athletes should perform trunk stabilization and neuromuscular control exercises at least 3–4 times per week. These exercises may vary depending on the sport that the athlete is returning to but generally should involve exercises that incorporate control of trunk rotation, weight bearing, and multiple angles of hip flexion. Such exercises could include low to high wood chops, high to low wood chops, rotating core planks, physioball bridging with alternating leg holds and alternating hip position, or single-leg stand rotating reaches (Table 2) (see **Video**, **Supplemental Digital Content 2**, http://links.lww.com/SCJ/A7, labeled "Trunk Stabilization and Core Control Exercises") (35,52).

ECCENTRIC EXERCISES

The eccentric contraction basis for injury and the positive prophylactic effect of eccentric training strongly suggest that eccentric training should be a component of a reconditioning program upon return to sport. Alternative exercises, such as the eccentric box drops, eccentric loaded lunge drops, eccentric forward pulls, split-stance Zerchers, and single-leg deadlifts, may be good alternatives to the Nordic curls because these exercises create biarticular muscle function in a unilateral asymmetric fashion, similar to that needed for sprinting and most sport activities (Table 3) (see **Video**, **Supplemental Digital Content 3**, http://links.lww.com/SCJ/A8, labeled "Eccentric Training Exercises") (11).

SUMMARY

Given the frequency of hamstring injuries and the high rate of injury recurrence, successful recovery and return to sport pose a great challenge to the rehabilitation professional and sports performance professional. Understanding the morphological and functional effects of injury can help optimize rehabilitation and reconditioning strategies. As outlined in this article, determining appropriate readiness for sport, using an appropriate dynamic warm-up program, integrating neuromuscular control and trunk stabilization exercises into sports performance programs, and the use of functional eccentric strengthening have shown potential to prevent a recurrent injury and keep athletes in the game.


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REFERENCES

1. Arnason A, Andersen TE, Holme I, Engebretsen L, and Bahr R. Prevention of hamstring strains in elite soccer: An intervention study. *Scand J Med Sci Sports* 18: 40–48, 2008.
2. Askling C, Karlsson J, and Thorstensson A. Hamstring injury occurrence in elite soccer players after preseason strength training with eccentric overload. *Scand J Med Sci Sports* 13: 244–250, 2003.
3. Askling C, Lund H, Saartok T, and Thorstensson A. Self-reported hamstring injuries in student-dancers. *Scand J Med Sci Sports* 12: 230–235, 2002.
4. Askling C, Tengvar M, Saartok T, and Thorstensson A. Sports related hamstring strains–Two cases with different etiologies and injury sites. *Scand J Med Sci Sports* 10: 304–307, 2000.
5. Askling CM, Tengvar M, Saartok T, and Thorstensson A. Acute first-time hamstring strains during high-speed running: A longitudinal study including clinical and magnetic resonance imaging findings. *Am J Sports Med* 35: 197–206, 2007.
6. Bennell K, Tully E, and Harvey N. Does the toe-touch test predict hamstring injury in Australian rules footballers? *Aust J Physiother* 45: 103–109, 1999.
7. Best TM and Hunter KD. Muscle injury and repair. *Phys Med Rehabil Clin N Am* 11: 251–266, 2000.
8. Best TM, Shehadeh SE, Leverson G, Michel JT, Corr DT, and Aeschlimann D. Analysis of changes in mRNA levels of myoblast- and fibroblast-derived gene products in healing skeletal muscle using quantitative reverse transcription-polymerase chain reaction. *J Orthop Res* 19: 565–572, 2001.
9. Brockett CL, Morgan DL, and Proske U. Predicting hamstring strain injury in elite athletes. *Med Sci Sports Exerc* 36: 379–387, 2004.
10. Brooks JH, Fuller CW, Kemp SP, and Reddin DB. Incidence, risk, and prevention of hamstring muscle injuries in professional rugby union. *Am J Sports Med* 34: 1297–1306, 2006.
11. Brughelli M and Cronin J. Preventing hamstring injuries in sport. *Strength Cond J* 30(1): 55–64, 2008.
12. Brughelli M, Cronin J, Mendiguchia J, Kinsella D, and Nosaka K. Contralateral leg deficits in kinetic and kinematic variables during running in Australian rules football players with previous hamstring injuries. *J Strength Cond Res* 24: 2539–2544, 2010.
13. Cameron M, Adams R, and Maher C. Motor control and strength as predictors of hamstring injury in elite players of Australian football. *Phys Ther Sport* 4: 159–166, 2003.
14. Cameron ML, Adams RD, Maher CG, and Misson D. Effect of the HamSprint Drills training programme on lower limb neuromuscular control in Australian football players. *J Sci Med Sport* 12: 24–30, 2009.
15. Canale ST, Cantler ED Jr, Sisk TD, and Freeman BL III. A chronicle of injuries of an American intercollegiate football team. *Am J Sports Med* 9: 384–389, 1981.
16. Chumanov ES, Heiderscheit BC, and Thelen DG. The effect of speed and influence of individual muscles on hamstring mechanics during the swing phase of sprinting. *J Biomech* 40: 3555–3562, 2007.
17. Connell DA, Schneider-Kolsky ME, Hoving JL, Malara F, Buchbinder R, Koulouris G, Burke F, and Bass C. Longitudinal study comparing sonographic and MRI assessments of acute and healing hamstring injuries. *AJR Am J Roentgenol* 183: 975–984, 2004.
18. Croisier JL, Ganteaume S, Binet J, Genty M, and Ferret JM. Strength imbalances and prevention of hamstring injury in professional soccer players: A prospective study. *Am J Sports Med* 36: 1469–1475, 2008.
19. Cross KM, Gurka KK, Conaway M, and Ingersoll CD. Hamstring strain incidence between genders and sports in NCAA. *Athl Train Sports Health Care* 3: 124–130, 2010.
20. De Smet AA and Best TM. MR imaging of the distribution and location of acute hamstring injuries in athletes. *AJR Am J Roentgenol* 174: 393–399, 2000.
21. Engebretsen AH, Myklebust G, Holme I, Engebretsen L, and Bahr R. Prevention of injuries among male soccer players: A prospective, randomized intervention study targeting players with previous injuries or reduced function. *Am J Sports Med* 36: 1052–1060, 2008.
22. Engebretsen AH, Myklebust G, Holme I, Engebretsen L, and Bahr R. Intrinsic risk factors for hamstring injuries among male soccer players: A prospective cohort study. *Am J Sports Med* 38: 1147–1153, 2010.
23. Feeley BT, Kennelly S, Barnes RP, Muller MS, Kelly BT, Rodeo SA, and Warren RF. Epidemiology of National Football League training camp injuries from 1998 to 2007. *Am J Sports Med* 36: 1597–1603, 2008.
24. Gabbe BJ, Bennell KL, Finch CF, Wajswelner H, and Orchard JW, Predictors of hamstring injury at the elite level of Australian football. *Scand J Med Sci Sports* 16: 7–13, 2006.
25. Gabbe BJ, Branson R, and Bennell KL. A pilot randomised controlled trial of eccentric exercise to prevent hamstring injuries in community-level Australian football. *J Sci Med Sport* 9(1–2): 103–109, 2006.
26. Gabbe BJ, Finch CF, Bennell KL, and Wajswelner H. Risk factors for hamstring injuries in community level Australian football. *Br J Sports Med* 39: 106–110, 2005.
27. Gabbe BJ, Finch CF, Wajswelner H, and Bennell KL. Predictors of lower extremity injuries at the community level of Australian football. *Clin J Sport Med* 14: 56–63, 2004.
28. Gambetta V and Benton D. A systematic approach to hamstring prevention and rehabilitation. *Sports Coach* 28(4): 1–6, 2006.
29. Garrett WE Jr. Muscle strain injuries. *Am J Sports Med* 24(6 Suppl): S2–S8, 1996.
30. Garrett WE Jr, Rich FR, Nikolaou PK, and Vogler JB III. Computed tomography of hamstring muscle strains. *Med Sci Sports Exerc* 21: 506–514, 1989.

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31. Garrett WE Jr, Safran MR, Seaber AV, Glisson RR, and Ribbeck BM. Biomechanical comparison of stimulated and nonstimulated skeletal muscle pulled to failure. *Am J Sports Med* 15: 448–454, 1987.

32. Gibbs NJ, Cross TM, Cameron M, and Houang MT. The accuracy of MRI in predicting recovery and recurrence of acute grade one hamstring muscle strains within the same season in Australian rules football players. *J Sci Med Sport* 7: 248–258, 2004.

33. Hagel B. Hamstring injuries in Australian football. *Clin J Sport Med* 15: 400, 2005.

34. Heiderscheit BC, Hoerth DM, Chumanov ES, Swanson SC, Thelen BJ, and Thelen DG. Identifying the time of occurrence of a hamstring strain injury during treadmill running: A case study. *Clin Biomech (Bristol, Avon)* 20: 1072–1078, 2005.

35. Heiderscheit BC, Sherry MA, Silder A, Chumanov ES, and Thelen DG. Hamstring strain injuries: Recommendations for diagnosis, rehabilitation, and injury prevention. *J Orthop Sports Phys Ther* 40: 67–81, 2010.

36. Heiser TM, Weber J, Sullivan G, Clare P, and Jacobs RR. Prophylaxis and management of hamstring muscle injuries in intercollegiate football players. *Am J Sports Med* 12: 368–370, 1984.

37. Jarvinen TA, Jarvinen TL, Kaariainen M, Kalimo H, and Jarvinen M. Muscle injuries: Biology and treatment. *Am J Sports Med* 33: 745–764, 2005.

38. Jonhagen S, Nemeth G, and Eriksson E. Hamstring injuries in sprinters. The role of concentric and eccentric hamstring muscle strength and flexibility. *Am J Sports Med* 22: 262–266, 1994.

39. Kaariainen M, Jarvinen T, Jarvinen M, Rantanen J, and Kalimo H. Relation between myofibers and connective tissue during muscle injury repair. *Scand J Med Sci Sports* 10: 332–337, 2000.

40. Koulouris G, Connell DA, Brukner P, and Schneider-Kolsky M. Magnetic resonance imaging parameters for assessing risk of recurrent hamstring injuries in elite athletes. *Am J Sports Med* 35: 1500–1506, 2007.

41. Kraemer R and Knobloch K. A soccer-specific balance training program for hamstring muscle and patellar and achilles tendon injuries: An intervention study in premier league female soccer. *Am J Sports Med* 37: 1384–1393, 2009.

42. Lee MJ, Reid SL, Elliott BC, and Lloyd DG. Running biomechanics and lower limb strength associated with prior hamstring injury. *Med Sci Sports Exerc* 41: 1942–1951,2009.

43. Lynn R and Morgan DL. Decline running produces more sarcomeres in rat vastus intermedius muscle fibers than does incline running. *J Appl Physiol* 77: 1439–1444, 1994.

44. Nikolaou PK, Macdonald BL, Glisson RR, Seaber AV, and Garrett WE Jr. Biomechanical and histological evaluation of muscle after controlled strain injury. *Am J Sports Med* 15: 9–14, 1987.

45. Orchard J. Biomechanics of muscle strain injury. *New Zeal J Sports Med* 30: 92–98, 2002.

46. Orchard JW and Best TM. The management of muscle strain injuries: An early return versus the risk of recurrence. *Clin J Sport Med* 12: 3–5, 2002.

47. Orchard J, Marsden J, Lord S, and Garlick D. Preseason hamstring muscle weakness associated with hamstring muscle injury in Australian footballers. *Am J Sports Med* 25: 81–85, 1997.

48. Proske U, Morgan DL, Brockett CL, and Percival P. Identifying athletes at risk of hamstring strains and how to protect them. *Clin Exp Pharmacol Physiol* 31: 546–550, 2004.

49. Purslow PP. The structure and functional significance of variations in the connective tissue within muscle. *Comp Biochem Physiol A Mol Integr Physiol* 133: 947–966, 2002.

50. Schache AG, Wrigley TV, Baker R, and Pandy MG. Biomechanical response to hamstring muscle strain injury. *Gait Posture* 29: 332–338, 2009.

51. Schneider-Kolsky ME, Hoving JL, Warren P, and Connell DA. A comparison between clinical assessment and magnetic resonance imaging of acute hamstring injuries. *Am J Sports Med* 34: 1008–1015, 2006.

52. Sherry MA and Best TM. A comparison of 2 rehabilitation programs in the treatment of acute hamstring strains. *J Orthop Sports Phys Ther* 34: 116–125, 2004.

53. Silder A, Heiderscheit BC, Thelen DG, Enright T, and Tuite MJ. MR observations of long-term musculotendon remodeling following a hamstring strain injury. *Skeletal Radiol* 37: 1101–1109, 2008.

54. Silder A, Reeder SB, and Thelen DG. The influence of prior hamstring injury on lengthening muscle tissue mechanics. *J Biomech* 43: 2254–2260, 2010.

55. Silder A, Thelen DG, and Heiderscheit BC. Effects of prior hamstring strain injury on strength, flexibility, and running mechanics. *Clin Biomech (Bristol, Avon)* 25: 681–686, 2010.

56. Slavotinek JP, Verrall GM, and Fon GT. Hamstring injury in athletes: Using MR imaging measurements to compare extent of muscle injury with amount of time lost from competition. *AJR Am J Roentgenol* 179: 1621–1628, 2002.

57. Telhan G, Franz JR, Dicharry J, Wilder RP, Riley PO, and Kerrigan DC. Lower limb joint kinetics during moderately sloped running. *J Athl Train* 45: 16–21, 2010.

58. Thelen DG, Chumanov ES, Hoerth DM, Best TM, Swanson SC, Li L, Young M, and Heiderscheit BC. Hamstring muscle kinematics during treadmill sprinting. *Med Sci Sports Exerc* 37: 108–114, 2005.

59. Van Don B. *Hamstring Injuries in Sprinting* [dissertation]. Exercise Science. Iowa City, IA: The University of Iowa; 1998.

60. Verrall GM, Slavotinek JP, Barnes PG, Fon GT, and Spriggins AJ. Clinical risk factors for hamstring muscle strain injury: A prospective study with correlation of injury by magnetic resonance imaging. *Br J Sports Med* 35: 435–439, 2001; discussion 440.

61. Woods C, Hawkins RD, Maltby S, Hulse M, Thomas A, and Hodson A. The Football Association Medical Research Programme: An audit of injuries in professional football–Analysis of hamstring injuries. *Br J Sports Med* 38: 36–41, 2004.

62. Worrell TW. Factors associated with hamstring injuries. An approach to treatment and preventative measures. *Sports Med* 17: 338–345, 1994.

63. Yu B, Queen RM, Abbey AN, Liu Y, Moorman CT, and Garrett WE. Hamstring muscle kinematics and activation during overground sprinting. *J Biomech* 41: 3121–3126, 2008.

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