Introduction

The hamstring complex is made up the biceps femoris, semimembranosus, and semitendinosus. Functionally, they work together to extend the hip and flex the knee during gait, especially during swing phase.[1] The hamstrings can also act as external and internal rotators of the leg due their insertions onto the lower leg. In terms of stabilization during functional activity and athletic movements, the hamstring group plays a role at both the hip and knee.[1] During sprinting activity, activation of the hamstrings controls hip movements during acceleration and protects the ACL during deceleration.[1] Neurologically, the hamstrings play a role in the ACL-hamstring reflex arc that provides afferent proprioceptive information.[2,3] With all of these functions (and certainly more), injury to the hamstring would affect full function. Proper prevention programs are needed to help athletes avoid injuries and good treatment plans are necessary to help athletes with hamstring injuries return to their sport activities. The purpose of this paper is to understand the epidemiology of hamstring injuries, identify risk factors, and present treatment and prevention program ideas that could help athletes maintain or resume their sporting activities after hamstring strain injuries.

Epidemiology of Hamstring Injuries

Hamstring strain injuries are the most common non-contact injuries in Australian football, American football, rugby union, soccer, and sprint events of track and field. Track and field reports 26% of their total injuries as hamstring strains, which is the highest amongst other sports. The percentage of hamstring strains reported in Australian football is 13-15%, with soccer at 12-14%.[4] American football training camps have reported 12% of total injuries are hamstring strain injuries.[4] Also, hamstring strains account for a high amount of lost playing time in cricket, rugby union, Gaelic football, and American football.[5] This would suggest that players, coaches, and team general managers might have an interest in reducing hamstring strain injuries on their sports teams for performance and economical reasons. While ankle sprains in soccer and posterior cruciate ligament injuries in Australian football have decreased with preventative injury programs, the rates of hamstring strain injuries have not decreased.[4] This suggests that preventative programs may not be targeting the risk factors necessary to decrease hamstring strain injury rates. Hamstring re-injury rates are alarmingly high, with reports of 16-60% recurrence rates amongst American football, rugby union, soccer, sprint events in track and field, and Australian football.[5] Rehabilitation protocols must be scrutinized to determine their weaknesses as well.

Mechanisms of Hamstring Injury

Opar et al (2012) has suggested that high muscle strain and/or high eccentric force are the main causes of hamstring strain injury.[4] High-speed acceleration and running activities (i.e. sprinting) where lengthening of the hamstrings exceeds the mechanical strength of the muscle, resulting in excessive extension of the muscle tissue, appears to be the predominant mechanism of hamstring strain injuries.[4,6] During sprinting, this most frequently occurs during the swing phase where significant elongation stress is placed on the hamstring muscle due to simultaneous hip flexion and knee extension.[7,8] Kicking has also been implicated in severe hamstring injuries as rapid, forceful lengthening of the hamstring also occurs.[7] Tackling, cutting, and slow-speed stretching have also resulted in a hamstring strain injury, particularly if eccentric loads are high enough.[4] When a hamstring strain injury occurs, they are characterized by acute pain in the posterior thigh resulting from damage to the hamstring muscle fibers.[4] These injuries present with a wide range of damage to the hamstring muscles, from full thickness tears requiring surgery, to microscopic tears resulting is little loss of function.[4] Whether or not accumulation of microdamage (via tendinopathy, etc) is a contributor to hamstring strain injury remains to be proven directly, but it seems plausible, especially for athletes in a fatigued state.[4] Evidence of increased muscle strains during NFL training camp[9] and altered inter-muscular coordination with fatigue[10] certainly point to the possibility.

The hamstrings are active during the entire gait cycle, but during the swing phase of sprinting the semitendinosus and biceps femoris are most active. They act as synergists to slow down knee extension, by eccentrically contracting, and initiate hip extension.[4,5,11] The biceps femoris appears to be active primarily during middle to late swing phase, while the semitendinosus is primarily active at terminal swing phase.[8] Terminal swing phase is when the hamstrings are at their maximum length, placing the most strain on the hamstrings.[4] The combination of the hamstrings at their greatest length and most active during the terminal swing phase, places them at risk for injury.[4] The most commonly injured location of the hamstring muscles is the biceps femoris muscle-tendon junction.[8] Efficient neuromuscular and intramuscular coordination patterns are required between the hamstring muscles to effectively slow down the lower leg during the swing phase.

Risk Factors of Hamstring Strain

Determining risk factors associated with hamstring injuries could help lead to the prevention of these injuries. According to a systematic review and meta-analysis by Freckleton et al (2013), systematic review by Opar et al (2012), and a review by Fyfe et al (2013), the most consistently supported risk factors associated with hamstring strain injuries are age, previous hamstring injury and asymmetrical knee flexion strength between bilateral limbs.[4,5,7] Additional risk factors with inconsistent evidence includes hamstring range of motion, body weight, hip flexor extensibility, hamstring and quadriceps peak torque, and knee flexion peak torque angle.[5,7] However, poor and inconsistent methodology or small sample sizes limit support for these risk factors at this time.[7]

Anatomical Considerations. The hamstrings are a bi-articular muscle that can be shortened and lengthened simultaneously at the origin and insertion point. This means that during movements where hip flexion and knee extension occur, like sprinting and kicking, more force is placed on the muscle.[4] Cadaver studies have revealed that the two heads of the biceps femoris have different architecture, possibly predisposing them to injury. The short head of biceps femoris has much longer muscle fascicles, allowing greater muscle extensibility compared to the long head.[6] Also, the long of the biceps femoris undergoes the greatest length change during sprinting activities, possibly predisposing it to damage.[4] Each of these may contribute to the biceps femoris being the most frequently injured hamstring muscle.

Age. Numerous studies have shown that age is a significant risk factor for hamstring strain injury.[4,7] Freckleton et al performed a meta-analysis with three studies that used risk ratio as their data and found that athletes 25 years or older have a 2.46 greater risk of hamstring strain injury compared to their younger counterparts.[7] While age is a risk factor, underlying mechanisms are less clear.[4]

Anthropometric Characteristics. Body mass index and height do not appear to be associated with an increased risk of hamstring injury.[7] A trend that increasing weight may contribute to increased hamstring injuries has been found, however, there was no statistical significance.[7]

Strength Parameters. Strength parameters can be divided into the following categories: 1) knee flexor (hamstring) weakness, 2) asymmetrical knee flexor strength between limbs and 3) low hamstring to quadriceps ratios (H:Q ratio) suggesting an inability of the hamstrings to oppose a quadriceps force.[4] At this point, there is conflicting evidence regarding knee flexor weakness as being a risk factor for hamstring strain in human, in vivo, studies.[4,5,7] It would seem likely that stronger hamstring muscles could provide better protection against strain injury, but a clear link has not been established in the evidence. There is evidence in the literature that using eccentric hamstring exercises, especially the Nordic curl (see figure 1), can decrease the incidence of hamstring injury and recurrence in soccer players.[12,13] However, neither study tested whether eccentric hamstring strength actually changed as a result of the exercise protocol. Interestingly, increased quadriceps peak torque was reported as a risk factor by Freckleton et al (2013).[7] When examining asymmetrical knee flexor strength, there is evidence of increased risk of a hamstring strain.[4,5,7,14] In a population of soccer players, untreated strength imbalances increased the risk of hamstring strain injury four to five times compared to players without imbalance.[15] Asymmetry of greater than 10% was a predictor of hamstring injury in American football players, greater than 8% in Australian football players, and greater than 15% in soccer players.[4] Low H:Q ratio has been suggested as a risk factor for years, but there is conflicting empirical evidence to support the claim. Freckleton et al suggest that at various speeds, angles, and contraction types, an association between low H:Q ratio and hamstring strain injuries has yet to be established based on studies reviewed.[7] However, Fyfe et al (2013) makes the argument that the protective effects of increasing H:Q ratios in numerous studies supports a low H:Q ratio as a risk factor for hamstring strain injury.[5] Opar et al (2012) also found conflicting results. Based on this evidence, it appears that hamstring strength imbalances show the greatest evidence as a risk factor.

Range of Motion Parameters. Mixed results show limited support for range of motion deficits being a risk factor for hamstring strain, but the majority of evidence shows no association.[5,7] Using the active knee extension test, decreased hamstring length was not identified as a risk factor for hamstring strain injury. Similarly, decreased range of motion via the passive knee extension test did not identify decreased hamstring range of motion as a risk factor.[7] However, in soccer players, there is evidence to suggest decreased knee extensor length can increase the chance of hamstring injuries.[7] Interestingly, there is some evidence that decreased hip extension from tight hip flexors could be associated with hamstring injury.[7] Lastly, pelvic position has been proposed as a risk factor because excessive anterior pelvic tilt would place the hamstring muscles in a lengthened position, possibly increasing the risk of strain injury.[4] However, scientific evidence is lacking.

Previous Injury. Previous hamstring injury appears to be the strongest risk factor for recurrent hamstring muscle strain, with strong empirical evidence to support.[4,7,16] The risk of injury has been reported to increase nearly 12-times the following season when a soccer player suffers a hamstring strain injury.[4]

Initial hamstring injuries could lead to changes that predispose the muscle to re-injury. It has been suggested that scar tissue development, muscle weakness, selective hamstring atrophy, and changes in torque-angle relationships are risk factors for re-injury.[4,5] However, the retrospective nature of many of these investigations make it unclear whether these factors were already present prior to a hamstring strain injury.[4] Inelastic scar tissue formation during muscle healing could lead to increased strain on in-series muscle fascicles, potentially increasing the risk of injury.[4,5] Silder et al (2008) suggest that scarring can continue up to 23 months after an injury and continue to alter contraction mechanics of the muscle.[17] The importance of inter-muscle coordination has already been highlighted, and disruptions could increase the risk of muscle strain injury. Altered activation patterns of the hamstring muscle group following an injury tend to result in a more symmetrical activation of the three muscles during a leg curl task.[8] This lack of muscle activation variability results in more inefficient muscle functioning, theoretically resulting in more stress and fatigue on the hamstring muscle group and potential for injury.[8] This altered activation could be to spare the injured muscle from producing force, leading to selective strength loss and atrophy of that muscle.[18]

Muscle that is weak due to low activation, atrophy, or fatigue can be injured more easily compared to stronger and less fatigued muscle.[10] Following hamstring injury, the eccentric strength of the muscle is compromised.[4] If proper rehabilitation is not enacted, this weakness could persist, putting an athlete at risk of re-injury.[5] Also, this could contribute to asymmetrical hamstring strength, which has already been discussed as a risk factor for hamstring strain injury.[5,7,15] Neuromuscular inhibition has been proposed as a mechanism for eccentric hamstring strength deficits found after hamstring strain injuries, and could be a reason for re-injury.[5] Selective atrophy of injured muscle also appears possible. Silder et al (2008) reported atrophy of the long head of the biceps femoris, where most hamstring strain injuries occur, and hypertrophy of the short head of the biceps femoris.[17] Decreased muscle cross sectional area could correspond to a decreased ability to attenuate eccentric forces, therefore increasing the risk of injury.

Changes in peak torque angle are also a risk factor with hamstring strain injury. Following hamstring strain injury, greater peak torque of the knee flexors occurred at shorter lengths, making the muscle more prone to damage from eccentric exercise and increasing the risk of re-injury.[19] Considering all of these potential problems with strain injury to the hamstring musculature, proper rehabilitation is critical to prevent future injury. There is also evidence to suggest that history of anterior cruciate ligament reconstruction, calf strain, and history osteitis pubis are related to increased risk of hamstring strain injuries.[7]

Treatment and Prevention of Hamstring Strain Injuries

The acute phases of muscle healing and rehabilitation have already been discussed in the course. To briefly review, if an athlete suffers a hamstring strain injury, it's very important to eliminate activation of the muscle and to place it in a shortened position so that the ends of the strained muscle are as close together as possible.[20] For the hamstring, it would mean using crutches to eliminate weight bearing while stabilizing the leg with some kind of brace to minimize hip flexion and knee extension. During this short period of immobilization, rest, ice, and compression should be employed to minimize swelling to the area, as this can further damage the tissue.[20] Within 5-7 days, movement can be introduced, starting with passive motion and progressing to active motion within non-painful limits. If significant pain still exists after this timeframe, further medical attention may be required.[20] From here, progression towards functional activity resumes by continuing to provide a healing environment, restoration of range of motion and strength, and introduction of neuromuscular control with sport-specific tasks. The length of time required preparing an athlete for their return to sport is challenging to predict.

After the muscle has healed sufficiently to begin reconditioning, focus should turn to improving functional performance of the hamstring musculature within the lower extremity kinetic chain. Guex and Millet (2013) have proposed a conceptual framework for exercises to prevent hamstring strains.[21] This framework focuses on addressing modifiable risk factors mentioned previously, including knee flexion weakness, bilateral asymmetry, low H:Q ratio, and increased peak knee flexion torque angle.[21] In terms of exercise choices to accomplish this, the authors focus on six key parameters: 1) contraction type, 2) load, 3) range of motion, 4) angular velocity, 5) uni-/bilateral exercises, and 6) kinetic chain. A number of studies have implemented treatment and prevention programs that have focused primarily on one or a few of these key parameters, like eccentric exercises or range of motion. For example, Guex and Millet (2013) discuss six studies that focus only on eccentric contraction using the Nordic hamstring exercise (see figure 1) or the yo-yo hamstring curl.[21] In these studies, a meaningful 60-70% reduction in hamstring strain injury occurred, but hamstring strain injuries still occurred, suggesting that not all of the risk factors were accounted for. In Petersen et al (2011), a season injury rate of 4 per 100 players occurred in the intervention group focusing solely on eccentric exercise compared to 13 per 100 players in the control group who did not use any exercise.[12] Certainly, it could not be expected to eliminate all hamstring strain injuries, but patients do deserve a comprehensive exercise regimen based on the best available data.

Contraction Type. With contraction type, eccentric training would be suggested based on the injury mechanism data presented thus far. The Nordic hamstring exercise (see figure 1) was devised to specifically place the hamstrings under an eccentric load. This type of eccentric training has been shown to effectively increase eccentric hamstring strength and decrease the peak torque angle, two risk factors associated with hamstring strain injury.[21] A study by Mjolsnes et al (2004) investigated the benefits of a 10-week eccentric training program using the Nordic hamstring exercise compared to a concentric training program using a machine leg curl in well-trained soccer players. Results showed an 11% increase in maximal eccentric hamstring torque and a 7% increase in maximal isometric hamstring torque for the players in the Nordic hamstring group.[22] The hamstring curl group demonstrated no significant increases in eccentric or isometric hamstring strength, however the subjects were asked to avoid any use of the hamstring in the eccentric phase.[22] This suggest that there are contraction-specific adaptations occur with training and it is important to consider this when implementing treatment and prevention programs for hamstring strain injuries. Another possible exercise choice are various types of bilateral and unilateral box drops (see figure 2 & 3). These exercises were successfully employed in a case series to decrease peak torque knee flexion angle in Australian Rules football players.[23]

Load. Load is the second parameter that Guex and Millet present. Since asymmetrical weakness of bilateral hamstrings is a modifiable risk factor, strengthening exercise targeting the weak hamstring would be advisable. This can only be done with progressive loading of the muscle. Load is simply the weight assigned to an exercise set.[21] Beginners to strength training do not require as much load compared to well-trained individuals. In well-trained individuals, loads of 80-100% of 1RM may be required to increase maximal muscular strength.[21] Therefore, progressive loading through rehabilitation and prevention programs are necessary to continually adapt the hamstring muscle to attenuate greater forces.

Range of Motion. During sprinting, the hamstrings go through significant lengthening, especially at terminal swing phase. During terminal swing phase, the hip flexes between 60-70 degrees, while the knee extends from 130 degrees (prior to terminal swing) of flexion to less than 30 degrees.[21] The semimembranosus, semitendinosus, and long head of the biceps femoris are stretched 9.8, 8.7, and 12.0% beyond their length in standing during terminal swing phase.[24] This combination of hip flexion and knee extension places considerable elongation stress on the muscle. Performing progressively loaded exercise in these lengthened positions could decrease the risk of hamstring strain injury. Askling et al has performed two randomized controlled trials on elite sprinters and jumpers and soccer players following hamstring strain that emphasized loaded lengthening in the intervention group.[25,26] This included exercises like “the diver” and “the glider” (see figures 4 & 5). The control group performed typical isolated flexibility exercises and strength exercises in less lengthened positions. Both studies resulted in faster return to sport and decreased re-injury rates for the loaded lengthening intervention compared to traditional flexibility exercises.[25,26] These studies, as well as studies demonstrating decreased knee peak torque angles, suggest that loading in lengthened ranges of motion can be protective against hamstring strain injuries.

Angular Velocity. Angular velocity refers to the speed of movement of the exercise. During fast running, peak hip flexion is greater than 700 degrees/second and peak knee extension is greater than 1000 degrees/second.[21] This means that the elongation velocity is extremely high. Replicating these angular velocities in rehabilitation and training is very difficult, and potentially dangerous. Fortunately, it has been shown that strength adaptations from eccentric training are independent of velocity of exercise. The Nordic hamstring exercise (see figure 1) is a low velocity movement shown to increase eccentric hamstring strength and decrease peak knee flexion torque angles.[21,27] A study by Iga et al (2012) demonstrated that use of the Nordic hamstring improved gains in eccentric peak torque at varying velocities (60 degrees/second to 240 degrees/second), despite the exercise being performed at a slower velocity.[27] This has been verified by other studies as well.[27–30] Considering that greater muscle damage can occur during faster eccentric exercises[31], having the ability to choose slow and moderate velocity exercises for our patients and still gain protection at higher velocities is useful.

Unilateral/Bilateral Exercises. A clinical evaluation may reveal bilateral or unilateral knee flexion torque weakness. In the case of unilateral hamstring weakness or bilateral hamstring asymmetry, targeted strengthening using unilateral, opposed to bilateral exercise, may be necessary to improve force production of the weakened hamstring without allowing the dominant limb to take over. A study by Croisier et al (2008) examined the effects of hamstring imbalances over the course of season.[15] They found a nearly 5 times greater risk of hamstring injury in athletes who had a 15% strength imbalance compared to athletes who did not have a bilateral asymmetry during pre-season testing.[15] To go further, in the same study, a group of athletes identified with an imbalance received an exercise program to promote hamstring strength symmetry. They were then retested to verify symmetry between hamstrings. With the restored symmetry, the athletes risk of hamstring injury was not statistically different than the group without an imbalance.[15] This study highlights the importance of identifying strength imbalances and correcting them. Using unilateral exercises could help with correcting these imbalances.

Kinetic Chain. The last parameter presented by Guex and Millet (2013) in exercise selection is the kinetic chain. This refers to open and closed kinetic chain exercises. Open chain exercises are described as those where the distal limb is free, while closed chain exercises have the distal limb fixed. In sprinting, the leg in terminal swing phase would be considered an open chain position. Therefore, the authors suggest it may useful to include open chain exercises in rehabilitation or prevention programs.[21] However, there is no empirical evidence to support what the author suggests and this appears to be the least important component. Numerous studies using combinations of open and closed chain exercises appear to be successful in reducing hamstring strain injury rates.[23,25,26,32] There is also considerable debate about the classification of open and closed chain exercises. For example, the Nordic hamstring exercise may be considered an open chain exercise because the feet are not directly fixed to the ground. However, others may consider it a closed chain exercise because the distal leg should be fixed during the movement. Regardless, at this point, there appears evidence that both open and closed chain exercises can aid in the prevention of hamstring injuries.

One aspect not discussed by Guex et al (2013) is the need for neuromuscular control. The need for proper inter-muscular coordination during sports activities has been previously discussed. Also, changes in muscle activation patterns following hamstring strain injury have also been discussed. Implementing exercises that require neuromuscular control would seem beneficial to athletes attempting to prevent or recover from hamstring strain injuries. A study by Sherry and Best (2004) compared the use of static stretching and isolated progressive hamstring exercise to progressive agility and stabilization exercises.[32] The later group clearly engaged the musculature in greater amounts of neuromuscular control. Results of the study showed that the group using progressive agility and stabilization exercises returned to sport quicker and had significantly less re-injuries within the first year after rehabilitation compared to the isolated stretch and strengthen group.[32] Using functional exercise to help prepare an athletes for returning to sport is very important.

Considering all of these parameters in rehabilitation or prevention program is important for athletes to maintain their health throughout a season. More research to identify pertinent risk factors, evaluation techniques, and prognostic indicators are necessary. Also, further evidence is required to on the best components of an intervention program. While this paper presents some of the available research and thinking on the subject, more work is still to be done to decrease the rates of hamstring injuries in sport.

References

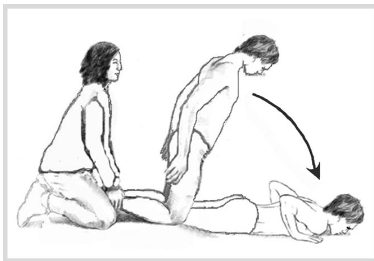
1. Kaeding CC, Borchers JR, eds. *Hamstring and Quadriceps Injuries in Athletes*. Boston, MA: Springer US; 2014. doi:10.1007/978-1-4899-7510-2.
2. Tsuda E, Okamura Y, Otsuka H, Komatsu T, Tokuya S. Direct evidence of the anterior cruciate ligament-hamstring reflex arc in humans. *Am J Sports Med*. 29(1):83–7. Available at: http://www.ncbi.nlm.nih.gov/pubmed/11206261. Accessed October 8, 2014.
3. Tsuda E, Ishibashi Y, Okamura Y, Toh S. Restoration of anterior cruciate ligament-hamstring reflex arc after anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2003;11(2):63–7. doi:10.1007/s00167-002-0338-3.
4. Opar D a, Williams MD, Shield AJ. Hamstring strain injuries: factors that lead to injury and re-injury. *Sports Med*. 2012;42(3):209–26. doi:10.2165/11594800-000000000-00000.
5. Fyfe JJ, Opar DA, Williams MD, Shield AJ. The role of neuromuscular inhibition in hamstring strain injury recurrence. *J Electromyogr Kinesiol*. 2013;23(3):523–30. doi:10.1016/j.jelekin.2012.12.006.
6. Kumazaki T, Ehara Y, Sakai T. Anatomy and physiology of hamstring injury. *Int J Sports Med*. 2012;33(12):950–4. doi:10.1055/s-0032-1311593.
7. Freckleton G, Pizzari T. Risk factors for hamstring muscle strain injury in sport: a systematic review and meta-analysis. *Br J Sports Med*. 2012:351–358. doi:10.1136/bjsports-2011-090664.
8. Schuermans J, Van Tiggelen D, Danneels L, Witvrouw E. Biceps femoris and semitendinosus-teammates or competitors? New insights into hamstring injury mechanisms in male football players: a muscle functional MRI study. *Br J Sports Med*. 2014;48(22):1599–606. doi:10.1136/bjsports-2014-094017.
9. Feeley BT, Kennelly S, Barnes RP, et al. Epidemiology of National Football League training camp injuries from 1998 to 2007. *Am J Sports Med*. 2008;36(8):1597–603. doi:10.1177/0363546508316021.
10. Abbaszadeh-Amirdehi M, Khademi-Kalantari K, Talebian S, Rezasoltani A, Hadian MR. The effect of fatigue and velocity on the relative timing of hamstring activation in relation to quadriceps. *J Bodyw Mov Ther*. 2012;16(4):488–92. doi:10.1016/j.jbmt.2012.07.002.

11. Schache AG, Kim H-J, Morgan DL, Pandy MG. Hamstring muscle forces prior to and immediately following an acute sprinting-related muscle strain injury. *Gait Posture*. 2010;32(1):136–40. doi:10.1016/j.gaitpost.2010.03.006.
12. Petersen J, Thorborg K, Nielsen MB, Budtz-Jørgensen E, Hölmich P. Preventive effect of eccentric training on acute hamstring injuries in men's soccer: a cluster-randomized controlled trial. *Am J Sports Med*. 2011;39(11):2296–303. doi:10.1177/0363546511419277.
13. Schache A. Eccentric hamstring muscle training can prevent hamstring injuries in soccer players. *J Physiother*. 2012;58(1):58. doi:10.1016/S1836-9553(12)70074-7.
14. Fousekis K, Tsepis E, Poulmedis P, Athanasopoulos S, Vagenas G. Intrinsic risk factors of non-contact quadriceps and hamstring strains in soccer: a prospective study of 100 professional players. *Br J Sports Med*. 2011;45(9):709–14. doi:10.1136/bjsm.2010.077560.
15. Croisier J-L, Ganteaume S, Binet J, Genty M, Ferret J-M. Strength imbalances and prevention of hamstring injury in professional soccer players: a prospective study. *Am J Sports Med*. 2008;36(8):1469–75. doi:10.1177/0363546508316764.
16. Van Beijsterveldt a MC, van de Port IGL, Vereijken a J, Backx FJG. Risk Factors for Hamstring Injuries in Male Soccer Players: A Systematic Review of Prospective Studies. *Scand J Med Sci Sports*. 2012:1–10. doi:10.1111/j.1600-0838.2012.01487.x.
17. Silder A, Heiderscheit BC, Thelen DG, Enright T, Tuite MJ. MR observations of long-term musculotendon remodeling following a hamstring strain injury. *Skeletal Radiol*. 2008;37(12):1101–9. doi:10.1007/s00256-008-0546-0.
18. Sole G, Milosavljevic S, Nicholson HD, Sullivan SJ. Selective strength loss and decreased muscle activity in hamstring injury. *J Orthop Sports Phys Ther*. 2011;41(5):354–63. doi:10.2519/jospt.2011.3268.
19. Brockett CL, Morgan DL, Proske U. Predicting hamstring strain injury in elite athletes. *Med Sci Sports Exerc*. 2004;36(3):379–87. Available at: http://www.ncbi.nlm.nih.gov/pubmed/15076778. Accessed November 18, 2014.
20. Järvinen TA, Järvinen M, Kalimo H. Regeneration of injured skeletal muscle after the injury. *Muscles Ligaments Tendons J*. 2013;3(4):337–45. Available at: http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3940509&tool=pmcentrez&rendertype=abstract. Accessed December 4, 2014.
21. Guex K, Millet GP. Conceptual Framework for Strengthening Exercises to Prevent Hamstring Strains. *Sports Med*. 2013. doi:10.1007/s40279-013-0097-y.
22. Mjølsnes R, Arnason A, Østhagen T, Raastad T, Bahr R. A 10-week randomized trial comparing eccentric vs. concentric hamstring strength training in well-trained soccer players. *Scand J Med Sci Sports*. 2004;14(5):311–7. doi:10.1046/j.1600-0838.2003.367.x.
23. Brughelli M, Nosaka K, Cronin J. Application of eccentric exercise on an Australian Rules football player with recurrent hamstring injuries. *Phys Ther Sport*. 2009;10(2):75–80. doi:10.1016/j.ptsp.2008.12.001.
24. 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):647–58. doi:10.1249/MSS.0b013e318236a3d2.
25. 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):532–9. doi:10.1136/bjsports-2013-093214.
26. Askling CM, Tengvar M, Thorstensson A. Acute hamstring injuries in Swedish elite football: a prospective randomised controlled clinical trial comparing two rehabilitation protocols. *Br J Sports Med*. 2013;47(15):953–9. doi:10.1136/bjsports-2013-092165.

27. Iga J, Fruer CS, Deighan M, Croix MDS, James DVB. “Nordic” hamstrings exercise - engagement characteristics and training responses. *Int J Sports Med*. 2012;33(12):1000–4. doi:10.1055/s-0032-1304591.
28. Farthing JP, Chilibeck PD. The effect of eccentric training at different velocities on cross-education. *Eur J Appl Physiol*. 2003;89(6):570–7. doi:10.1007/s00421-003-0841-3.
29. Ryan LM, Magidow PS, Duncan PW. Velocity-specific and mode-specific effects of eccentric isokinetic training of the hamstrings. *J Orthop Sports Phys Ther*. 1991;13(1):33–9. doi:10.2519/jospt.1991.13.1.33.
30. Duncan PW, Chandler JM, Cavanaugh DK, Johnson KR, Buehler AG. Mode and speed specificity of eccentric and concentric exercise training. *J Orthop Sports Phys Ther*. 1989;11(2):70–5. Available at: http://www.ncbi.nlm.nih.gov/pubmed/18796927. Accessed December 4, 2014.
31. Chapman D, Newton M, Sacco P, Nosaka K. Greater muscle damage induced by fast versus slow velocity eccentric exercise. *Int J Sports Med*. 2006;27(8):591–8. doi:10.1055/s-2005-865920.
32. Sherry MA, Best TM. A comparison of 2 rehabilitation programs in the treatment of acute hamstring strains. *J Orthop Sports Phys Ther*. 2004;34(3):116–25. doi:10.2519/jospt.2004.34.3.116.

Figures

Figure 1.



The Nordic hamstring exercise. From Iga et al (2012).[27]

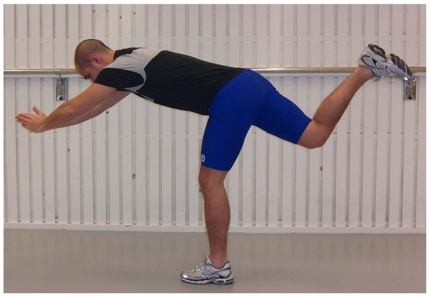
Figure 2.

Bilateral box jump. From Brughelli et al (2009).[23]

Figure 3.

Split, bilateral box drop. From Brughelli et al (2009).[23]

Figure 4.



"The Diver". From Askling et al (2014).[25]

Figure 5.

"The Glider". From Askling et al (2014).[25]