ASYMMETRICAL MUSCLE DEVELOPMENT IN SPECIALIZED ATHLETES AND ASSOCIATED INJURY RISK

By

KAYLA REBECCA DARRIS

A Thesis Submitted to The Honors College

In Partial Fulfillment of the Bachelors degree
With Honors In

Physiology

THE UNIVERSITY OF ARIZONA

APRIL 2016

Approved By:

Dr. Douglas Keen
Department of Physiology

Abstract

Hamstring strains and knee sprains are occurring in professional sports at an alarming rate that might suggest athletes are being subjected to increased injury risk. This increased risk may come from the asymmetric development of the quadriceps and hamstring muscle groups. Injury surveillance systems and individual studies have revealed a significant relationship between the rate of occurrence of lower limb injury and a low eccentric hamstring to concentric quadriceps strength ratio. Nevertheless, the current literature contains conflicting studies on the effects of sport-specific training on muscle development. While muscle asymmetries might play a role in injury risk, there has not yet been a proven association between sport-specific training and the development of muscle asymmetries. The results of multiple studies still suggest that hamstring and knee injuries can be prevented through the implementation of a balanced workout program and flexibility training.

Table of Contents

Introduction 1

NCAA Data Collection 1

Purpose and Research 2

Normal Structure and Function of Joints and Muscles 3

The Synovial Joint 3

Knee Joint Anatomy 6

Skeletal Muscle 7

Hamstring Muscle Anatomy 8

Muscle Force 10

Elastic Force 11

Joint Reaction Force 11

Development of Asymmetric Joints 12

Muscle Growth 12

Asymmetric Development 14

Quantification of Asymmetry 15

Effects of Sport Specific Training on Muscle Group Development 16

Cross-Joint Asymmetry and Injury Risk 20

Injury Occurrence in the NFL and MLB 20

The Fatigue Factor 23

Anterior Cruciate Ligament Tears 25

Lower Extremity Injury Screening and Prevention 26

Injury Screening 26

Application of Injury Screening: The NHL 28

Injury Prevention 28

Conclusion 29

References 31

Introduction

Professional sports have become an excessively lucrative market in the past few years. With the increases in revenue and consumer interest, the demand for elite athletes has skyrocketed. To meet this demand, aspiring athletes have begun to specialize at a very young age. This decision affects the way they train and the subsequent development of significant muscle groups. The result is maturing athletes that have more specific skill sets and a higher possibility of asymmetric antagonist muscles to accommodate for specific repetitive actions related to their sport. For example, a volleyball player who is constantly jumping relies more heavily on the extension provided by the quadriceps as opposed to the flexion movement of the hamstrings. However, asymmetric development may have negative effects on the ability to participate in sports. Mainly, it can increase the risk of muscle strains and ligament sprains due to the overpowering of a muscle group by its antagonist. This increased risk is seen frequently in professional sports and in college sports where the muscle groups have reached full, yet asymmetrical, development in elite athletes. A collection and analysis of injuries that occurred in collegiate sports revealed trends that might indicate asymmetric muscle development is to blame.

NCAA Data Collection

Between 2004 and 2009 the NCAA collected data on the injuries being sustained by student athletes with the goal of improving prevention techniques and athlete care. Almost all sports observed reported that injuries occurred most often to the lower extremities (men's soccer, 65.6%; women's soccer, 65.3%; women's volleyball, 51.5%; football, 50.4%) (Kerr). Their analysis of the data concluded that soccer players are uniquely susceptible to muscle and ligament strains and sprains due to quick changes of direction. Hamstrings and adductors were listed as especially susceptible to injury during play. In addition, women participating in the sport were significantly more susceptible to anterior cruciate ligament (ACL) tears and sprains then their male counterparts. For both men's and women's soccer, most injuries occurred in the second half of the contest, an indication that fatigue may be a factor.

Women's Volleyball statistics revealed some of the same trends. The explosive nature of the sport places a large amount of strain on the ligaments and muscle groups that make up the lower extremity. In fact, most injuries recorded were classified as acute non-contact, likely from issues landing or making an athletic move towards the ball. Prolonged overuse of muscles was the second highest reason for injury, but was more associated with injures to the shoulder muscle groups. Unlike soccer, however, the injuries were spread evenly from the pre-game warmup to the final set of the match. Nevertheless, rate of injury was much higher in the preseason than during the regular or postseason.

NCAA football recorded the most injuries of any college sport, with the knee being the most common location for injury (17.1% of all injuries). Surprisingly, the most cited reason for injury was acute noncontact, which may oppose the belief that football is dangerous because of the violent collisions involved. In addition, the study found that most injuries occurred during the preseason, even though players are seven times more likely to be injured in a game than in practice. Overall, the data collection showed that lower extremity injuries are occurring more frequently than injuries to any other anatomical locations. In addition, there is a trend across sports that the injury rate is higher in the preseason than at any other time of the year (Kerr).

Purpose and Research

The focus of most injury research is on the prevention, frequency, and treatment of concussions. However, the high rates of injuries to the lower extremities and their cause have been severely neglected. The purpose of this review is to assess current research on the high rate of knee injuries and discern that a contributing factor is the development of asymmetric antagonist muscle groups. The focus will be on the knee and lower extremity joints because the effects of imbalanced training are magnified across weight bearing joints. In addition, prevention and treatment methods will be reviewed for viability and effectiveness.

Normal Structure and Function of Joints and Muscles

The Synovial Joint

The 206 bones of the human body articulate with one another to from approximately 200 joints. These articulations are classified by the level of movability between the two connecting bones. Fibrous joints, which are found in the skull and between the bones of the forearm and shin, are relatively immovable. Slightly moveable joints are classified as cartilaginous and can be found between the intervertebral disks of the spine and at the pubic symphysis. The focus of this review is on the third type of joint: the freely moveable synovial joint that makes up the shoulders, knees, hips and other structures. These articulations allow for the freedom of movement that enable humans to jump, run, and throw (Enoka, 128). Due to their close relationship with movement and force production, synovial joints are often involved sports injuries.

Synovial joints serve two major functions in the body: skeletal mobility and force transmission. The major structures making up a synovial joint allow adjacent body segment to rotate around each other, thus producing body movement and flexibility. In addition, the geometry and muscle attachments of the joint will allow force to be transmitted from one body segment to another. Bones subjected to constant and strenuous movement must be protected from the friction caused by two adjacent bones grinding against each other. This function is performed by articular cartilage; a dense white connective tissue that can be seen in figure 1 (Enoka 128). While the major component of articular cartilage is water, the connective tissue also contains fine collagen fibrils and a concentrated solution of proteoglycans. The concentration of each substance is important in determining the cartilage's biomechanical behavior.

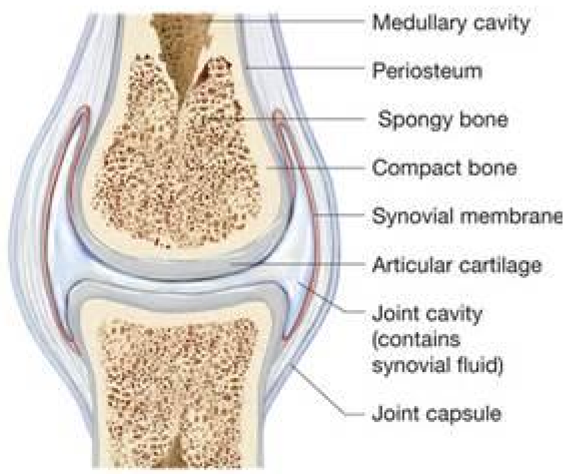


Figure 1. Major Component of a typical synovial joint

Articular cartilage is protected by two functioning forms of lubrication. The first, a boundary lubrication caused by the absorption of lubricin by the articular cartilage, is important when the contacting surface between joints are maintaining high loads for long periods of time. For this reason, boundary lubrication is abundant in weight bearing joints such as the knees and hips. In joints where the load is variable and contact surfaces move quickly relative to another there is a fluid film lubrication. This lubrication causes separation of the contact surfaces to reduce friction and allow for higher speed movements. These fluids are exuded in front of and beneath the moving contact surfaces but then are reabsorbed as the load passes, thus making synovial joints self-lubricating. The constant flux of fluid is thought to provide nutrients for the chondrocytes that provide the matrix for the cartilage (Enoka 129).

In order for articular cartilage to adequately protect the bones that make up the joint, it must respond to different loads and movement needs of the joint. The cartilage is subject to constant load and deformation so its response changes over time, making the cartilage a viscoelastic material. The thickness of the cartilage can change due to the stress-related flux of water. Athletes and other active individuals have thicker, more dynamic cartilages that thicken as one moves from the resting to active state. In the knee, a weight bearing joint under near constant stress, the articular cartilage specializes to form menisci to enlarge articulating surfaces and disperse the stress over a slightly larger area. The heaviest loads experienced by articular cartilage are supported by a collagen-proteoglycan matrix and the resistance of the fluid flow through the matrix (Enoka 129).

Since there is expulsion and reabsorption of fluid and lubrication around the contact surfaces of bone, the joint anatomy cannot be exposed to surrounding tissue. The articulating surfaces of synovial joints are enclosed within a joint capsule that attaches to the bones comprising the joint. In some cases, the capsule fuses with capsular ligaments to anchor the joint components within close proximity. The inner lining of the capsule and non-contact surfaces of bone are lined with synovial membrane. This membrane produces synovial fluid that provides nourishment and lubrication for the articular cartilage. Similar to articular cartilage, the synovial membrane and joint membrane are dynamic and respond to load and activity. In fact, connective tissue in general adapts to the shortest functional length, which makes joint immobilization for rehabilitation a risky process. Once the joint is immobilized, the capsule and ligaments shrink, with new tissue being synthesized to adjust to the shorter length. Even subtle changes will result in a reduction of mobility at the joint and the possible development of osteoarthritis.

The connective tissue surrounding the joint is a large factor in the quality and direction of motion produced by the joint. The architecture of the articulating surfaces and the design of the connective ligaments is collectively known as the joint geometry. This geometry can permit rotation about one to three axes. Each axis is known as a degree of freedom and can pass through the joint from side to side, front to back, or end to end. In addition this movement can be clarified by its movement in regards to the body. For example, joint movement can occur in a flexion-extension plane, abduction-adduction plane, or even as rotation around the longitudinal axis (Enoka, 56) The six types of synovial joints reflect their mechanism and their degrees of freedom. A planar or gliding joint is composed of two flat or slightly curved bones that can glide over each other. These joints are found in the carpals bones of the hand and the tarsal bones in the foot. A pivot joint is formed by a bone with a rounded end fitting into a ring formed by the other bone. The atlas vertebrae that allows for the movement of the skull is a prominent example of a pivot joint. The ball-and-socket joint allows for movement along all three axes as a "ball" end of one bone fits into a curved "socket" of the other. This allows for the flexion, extension and rotation found in the shoulder joint. The condyloid joint is very similar to ball-and-socket except that it allows rotation around two axes and is found in the wrist and finger joints. A saddle joint moves more freely than a condyloid joint as the convex portion of one bone fits with the concave portion of the other. This "saddle" formation allows for movement along two axes and is found in the thumb. Finally, the hinge joint, which makes up the elbow, is designed so that one bone moves while the other stays stationary. The knee is a considered a modified hinge joint as it has slightly more freedom of movement that a typical hinge joint.

Knee Joint Anatomy

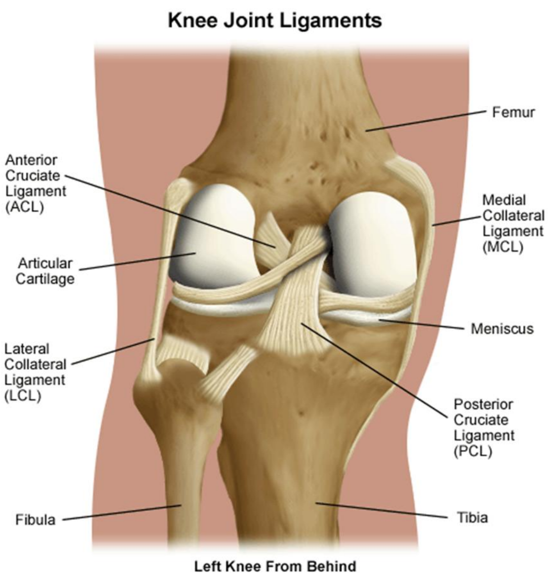


Figure 2. Posterior view of knee joint connective tissue

The knee joint is the connection of four bones through four major ligaments and two menisci. The joint itself is made up of the connection between the femur and the tibia. The fibula and the patella also make up the knee. The posterior collateral ligament (LCL) and the medial collateral ligament (MCL) attach the condyles of the .femur to those of the tibia on both the medial and lateral sides. In addition, the anterior cruciate ligament (ACL) and posterior cruciate ligament (PCL) are found between the condyles of the bones to prevent excessive anterior and posterior sliding of the femur and tibia heads. Within the joint capsule, there are two menisci, a lateral and medial, which act as shock absorbers for the joint reaction force transferred through the knee joint. The menisci are assisted by several bursae, or fluid filled sacs that help in knee support and shock absorption.

Skeletal Muscle

Movement throughout the human body is dependent on the ability of muscle to produce force across a joint. Specifically, voluntary movement is produced by skeletal muscle that is characterized by striations. The basic structural unit of muscle fiber is the sarcomere, which can convert chemical signals from the sarcoplasmic reticulum into mechanical contraction. Sarcomeres are repeating units that line up end to end to form a myofibril. Myofibrils form bundles that make up a single muscle fiber. Single muscle fibers are surrounded by a layer of connective tissue known as the endomysium. Muscle fibers are then grouped together by the perimysium to form fascicles which then group together to form the entire muscle, which is surrounded by the epimysium. The specific groupings of muscle allow individual and specific units to be recruited based on the amount of force needed for a specific movement. In fine motor muscles such as those that control the finger, this recruitment will be more precise than that of larger muscle groups such as the biceps femoris. In addition to providing organization and support, the connective tissue matrix found in muscle serves an important function at attachment sites. This matrix connects the muscle to the tendons, made entirely of connective tissue, that attach the muscles to bone. Referred to as the musculotendinous unit, it allows the muscle and tendon to act synchronously as a single functional unit. Each muscle has two points of attachment to bone. The first is referred to as the origin which does not move the bone that it is attached to. For instance, the biceps brachii muscle has two origins on the humerus bone, one for each head of the muscle. Even though the biceps brachii is connected to the humerus, its flexion does not cause the bone to move. The second point of muscle attachment is called the point of insertion. At this site, the contraction of the muscle will cause the bone to move. In our example, the biceps brachii point of insertion is the proximal radius. While every skeletal muscle in the body follows this basic structure, the next section will elaborate on the specifics of the hamstring muscle (Enoka 129).

Hamstring Muscle Anatomy

The hamstrings are actually a group of three muscles located posterior to the femur that are crucial in proper gait and running. The muscle group consists of the semitendinosus, biceps femoris, and semimembranous mucles. Each muscle measures about 43 centimeters from origin to insertion, with the exception of the short of the head of the biceps femoris which measures approximately 29 centimeters (Leimpanen). Proximally, the hamstring muscles origin is at the ischial tuberosity, with the exception of the short head of the biceps femoris, which attaches at the linea aspera of the femur (Perez-Bellmunt). Distally, the semitendinosus muscle runs along the medial posterior section of the leg to connect to the medial tibial tuberosity. The biceps femoris has two attachments points on the lateral side of the knee at the head of fibula and the lateral condyle of the tibia. The semimembranosus muscles also attaches on the medial condyle of the tibia.

The connective tissue matrix of the hamstring is not well understood, but some studies have suggested the presence of an annular structure that may act like a retinaculum. The proposed structures cover the origin of the proximal attachment of the hamstring muscles and receives loose connective tissue expansions from the epimysium of the gluteus maximus. Contrary to a retinaculum, however, the structure adheres tightly to the proximal attachment site and may be better classified as an anchor. The structure may also have a force transmission function. The anchor can help establish coordination between the long head of the biceps femoris and the gluteus maximus muscle (Perez-Bellmunt). In addition to the annular structure, the proximal and distal tendons make up a large part of the muscle itself, making the tendon structure more important in assessing injury. In fact, the proximal tendons of each muscle run between 29.4 to 72.7% of the entire muscle length while the distal tendons measure between 45.6 and 62.6% of the entire muscle length (Leimpanen). Essentially, the entire hamstring complex relies heavily on dense connective tissue for attachment and function. This could lead to the high risk of injury generated by muscle and joint reaction force.

Muscle Force

The gross role of a muscle is to exert a force transmitted through the tendon and bone to cause body segment rotation. Nevertheless, the pure physical definition of force cannot be applied to muscle because a muscle cannot push to alter a state of motion, it can only pull. Essentially, a muscle can generate tensile force, but is incapable of producing a compressible force. Since a muscle has only unidirectional capability, movement about a joint is controlled by several muscles referred to agonists and antagonists. While agonists will assist each other in a similar motion, antagonists will produce force in opposite directions around the same joint. For example, the elbow is controlled by one group that causes extension and another that causes flexion. These groups work together to produce a full range of motion. However, when other forces such as gravity are acting on the system flexion muscles can control extension through relaxation. In this way, the function of a muscle depends on the environment in which it is activated. In the absence of all other forces, the human body needs a minimum of two opposing muscle to produce each anatomical motion (Enoka 56).

The magnitude of force that each muscle can produce varies greatly throughout the human body. However, since the direct measurement of muscle force is an invasive procedure, the measure of the magnitude of force a muscle can produce is done through indirect measures. Most of the time, cross-sectional area of the muscle is used to calculate force. The cross-sectional area is derived from measuring the end-on view of a cadaver muscle that has been sectioned. Magnitude is also determined by the capacity of a muscle to produce force relative to cross-sectional area. This is a constant known as specific tension which varies between 16 and 40 N/cm^2. The equation for force magnitude is below:

$$F_m = ST \; x \; CSA$$

While specific tension is constant for different fiber types, the transmission of force from the cross-bridges to the tendon can vary among motor unit types. Antigravity muscles such as the hamstrings (knee extensors) are approximately twice as strong as their counterparts simply due to cross-sectional area. This difference may have some impact on overall body asymmetry.

Elastic Force

Pulling forces can increase the length of the tissue being stretched. The total stretch is dependent on the nature of the tissue and the magnitude of the pulling force. Biological tissue has its own elastic limits, where it can be stretched and expected to return to its original length. The elasticity of tissue differs based on tissue type, health, and age. To calculate this region, muscle are tested using strain percentage, or the change in length of the tissue relative to the initial length. If the deformation of the tissue extends beyond normal limits into the plastic region, the length it returns to will be longer than the initial length of the tissue. In tendons, the upper limit for physiological strain is 2 to 5% strain. At 8%, the tendon will break and cause serious injury. Most physiological deformations of tendons and other connective tissue are long term without surgical correction (Enoka 63).

Joint Reaction Force

Muscles not only exert tensile force on themselves and their connective tissue matrix, but they will exert a small amount of compressible force on the connecting bone. Joint reaction force is the net forces generated by bone-on-bone contact between adjacent body segments. If antagonist muscle groups are activated simultaneously, the joint reaction force is the difference in activity of the muscle, or the net force. This concept is important because the body is made up of rigid segments that are connected, a single force acting on one segment can be transmitted to all other segments. The feet and the knees are weight bearing joints that experience a large amount of joint reaction force and are subject to damage to the ligaments and other connective tissue that makes up the joint. However, the joint reaction force is dispersed throughout the entire body due to the connected body segments.

This force has been measured for everyday activities such as sitting, standing, walking, and running. Maximum forces are found at midstance during a run. The joint reaction force reached a compression force of thirty three times body weight at the knee joint and peak compressive force of nine times body weight. The ankle experienced a peak shear force of four times body weight. Standing after sitting is another action associated with large joint reaction forces. When standing, the knee joint experienced forces between 4.7 and 5.6 times body weight. These measurements show that joint reaction forces can vary greatly over range of motion and activity and can play a key part in injury occurrence (Enoka 64).

Development of Asymmetric Joints

Muscle Growth

Muscle growth can be classified into two different categories, hypertrophy and hyperplasia. As discussed earlier, the ability of a muscle to produce force is strongly related to the cross-sectional area of the muscle. Muscle hypertrophy is a direct increase to the cross-sectional area of individual muscle fibers. In contrast, an increase in the number of total muscle fibers is hyperplasia. Under most conditions, the primary mechanism for muscle growth is hypertrophy though hyperplasia can occur in some circumstances.

The extent of muscle growth is dependent upon the initial strength of the muscle, and the duration and type of contraction involved in training. Isometric or static training and eccentric-concentric or dynamic training will result in different levels of muscle hypertrophy. These types of contractions are classified by the total change in muscle length or the ratio of the magnitude of torque exerted by the muscle to the magnitude of torque generated by the load. If the muscle to load ratio is equal to one, then the muscle length will not change and the contraction is considered isometric. For example, simply clenching your fist or trying to push a heavy object would be classified as an isometric contraction. Dynamic training is a combination of concentric and eccentric contractions that can exercise the full movement about a joint. Concentric contractions are characterized by a muscle to load ratio that is greater than one which will result in a net shortening of whole muscle length. Eccentric contraction is essentially the opposite, with a muscle to load ratio that is less than one which will result in a longer whole muscle length. An example of eccentric exercise is the bicep curl, where the biceps brachii lengthen as the elbow extends. The greatest cross-sectional increase will be seen in novice subjects performing dynamic exercises. While dynamic exercise are still effective for experienced subjects, there will be less hypertrophy than in muscle of inexperienced subjects (Enoka 319).

On a molecular level, muscle hypertrophy requires a change in the ratio of protein synthesis to protein degradation. However, the mechanism controlling this ratio is not well known, but is dependent on potential stimuli from hormonal, metabolic, and mechanical factors. Hormonal stimuli include growth hormone (GH), insulin, and testosterone. The effects of a hormone will distribute throughout an entire muscle body, but the change in cross-sectional area can be limited to specific muscle fiber types or to one muscle. For this reason, hormonal stimulation is likely not the primary stimulus for muscle growth. Aerobic exercises, which are focused on metabolic factors cause a greater increase in endurance than in strength. The evidence suggests that mechanical stimuli are the primary factors in inducing hypertrophy. The mechanical stimulus mechanism involves the release of a second messenger when a stretch or contraction stimulus is applied. The second messenger then modulates the rates of the protein synthesis and degradation. Second messengers can be either extra-cellular matrix molecules or alterations in plasma membrane-associated molecules. These mechanical stimuli influence both the quality and quantity of synthesized muscle tissue. This is because the protein-isoform genes that are transcribed determine the muscle fiber phenotype that will be transcribed. By default, fast myosin heavy chains will be synthesized, but slow twitch fibers can be expressed under exercise regimes that elicit maximal force. These differences in gene expression mean that an identical training stimulus can result in different hypertrophic responses among different individuals (Enoka 320).

Asymmetric Development

Asymmetry across a muscle joint can be defined as the disproportionate growth of muscle antagonists. For the purposes of this review, the main focus is on asymmetry across the knee joint and the development of the quadriceps muscles versus that of the hamstrings. It is believed that sport specific training inadvertently places a greater emphasis on the development of the quadriceps over the hamstring muscle groups. This is because the quadriceps are dynamically activated while performing athletic activity. The quadriceps are contracted when entering a simple “ready position” seen in football, volleyball and even soccer. In both soccer and football, typical training and game play includes running, jumping and kicking that may promote disproportionate growth of the antagonist muscle groups (Pavlos). As athletes become more specialized and dedicated to their sport, the training becomes more intense so elite athletes are at higher risk of asymmetric muscle development. The hamstrings are often less stressed in training because routine activities in practice and games do not exercise the muscle to the extent that the quadriceps are stressed. Nevertheless, there is very little evidence in the existing literature to prove or disprove that this kind of training is a primary factor in the development of lower extremity muscles.

With the development of only one antagonist muscle, the transmission of force across the joint is also altered. Any change in the balance of force production across a joint will result in a change in the net directional force across the joint. This could result in differences to joint anatomy that could be permanent or temporary. For example, the ligaments surrounding the knee are subject to any forces passing through the joint. In particular, the anterior and posterior cruciate ligaments of the knee are sensitive to force changes in the anterior and posterior directions. In addition, a change in muscle balance will affect the joint reaction force passing through the knee. Changes in quadriceps and hamstring strength will affect the distribution of the joint reaction force across the medial and lateral condyle, epicondyles, and menisci. Changes in the force transferred across any of those structures could result in damage.

Quantification of Asymmetry

Muscle balance across the knee joint is usually measured using a peak torque ratio. The conventional ratio measured the peak concentric torque of each of these muscle groups. However, this ratio proved to be inaccurate because the true balance of the knee joint is determined by contraction of the quadriceps and extension of the hamstring. To adjust for this difference, the functional ratio was introduced in 1995 (Evangelidis). The ratio measures the peak concentric torque of the quadriceps versus the peak eccentric torque of the hamstrings. This method is a better reflection of the opposing functions of the muscle groups during activity. The functional ratio still had its limitations due to the fact that the quadriceps and hamstrings exhibit their peak torques at different angles. Since muscle strains will occur with the antagonist groups at the same angle, the torque of the muscles must be measured at the same angle to be accurate. To account for this, the functional ratio can be calculated through the full range of motion of the knee joint, with a special interest on the late-swing phase when the foot plants and the knee is at higher risk for injury. By measuring across the full range of motion, one could assess imbalances that are angle-specific and more pronounced at extended knee joint positions.

Effects of Sport Specific Training on Muscle Group Development

The effects of training at different levels of athletic competition have been well studied, but have yet to yield consistent results. The studies vary in key components such as sample size, subject sport and method of quantifying muscle force in the quadriceps and hamstrings. These types of studies are highly subject to variability in gene expression, metabolism, and environmental factors in test subjects making it nearly impossible to gather consistent data for statistical comparison. For example, two studies testing nearly identical hypotheses yielded near opposite results. In the first experiment, John Iga found significant differences in hamstring to quadriceps (H:Q) ratios between trained youth soccer players and untrained individuals. Nevertheless, in another study, Pavlos Evangelidis showed that here were no difference in the H:Q ratio of recreationally active males and football players.

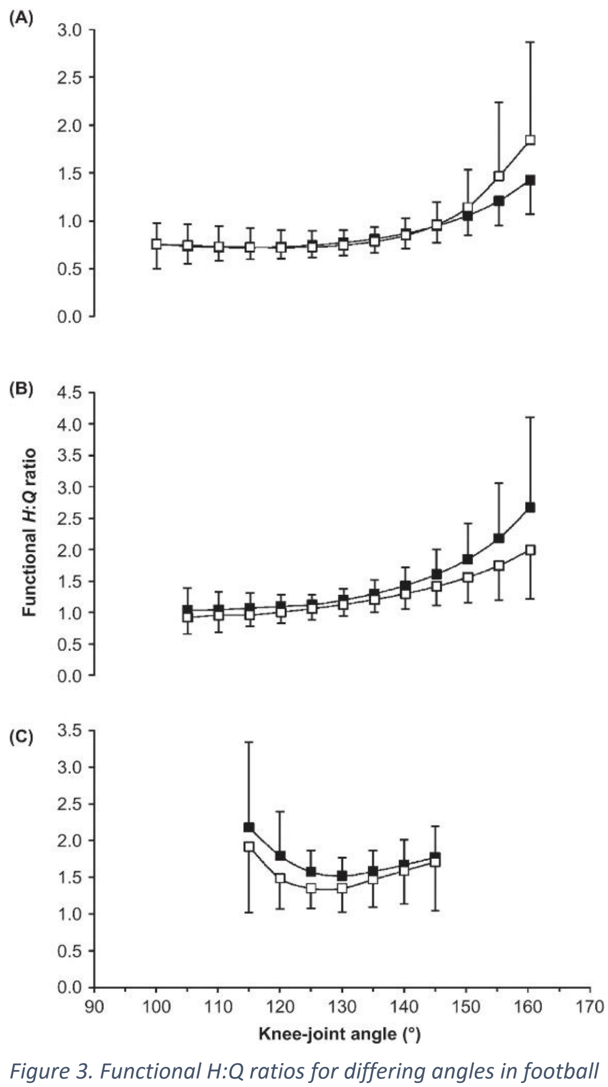


Figure 3. Functional H:Q ratios for differing angles in football players (Fb, filled squares) and controls (Con, open squares) at: (A) 60° s−1 (Fb, n = 10, Con, n = 14), (B) 240° s−1 (Fb, n = 9; Con, n = 13) and (C) 400° s−1 (Fb, n = 10, Con, n = 14). Mean + SD

The Evangelidis study compared ten collegiate football players to fourteen recreationally active males who volunteered to take part in the study. While the football players participated in four to five football training sessions per week and one to two strength training sessions per month, the control group members did not participate in any systematic strength training for the lower extremities. Each subject was tested for the H:Q ratio throughout the full range of motion of the dominant leg. As shown in figure 3, the full range of motion was tested at several speeds of isokinetic contraction at the lower extremities. The subjects with the best muscle symmetry will have higher H:Q ratios. If sport specific training was a major factor in the development of asymmetric antagonist muscles we would expect the control group to exhibit significantly higher H:Q ratios than their football player counterparts. However, the results gave no significant difference of functional H:Q ratios at any spend or angle of extension. At $60^{o}/s$, the control group had a slightly higher H:Q ratio at the angles of importance. The opposite proved to be true at $240^{o}/s$, where the football players actually had a higher H:Q ratio than the control group. Overall, investigators concluded that there was no significant difference between the healthy football players and the recreationally active males. The study is severely limited by the small sample size and the varying experience of the football players involved in the study. In addition, the study used "recreationally active males" as the control, when non-active individuals may have been a better baseline to compare results. A strength of the study was the inclusion of the full range of motion on measurement, including an emphasis on lower extremity extension angles that are more conducive of injury. The study provides a starting point for more studies to test the effects of football and strength training on the lower extremities at all extension angles.

The Iga study focused on athletes just starting their career, and thus focused on the impacts of muscle training on the beginning stages of muscle development and growth. In this experiment, subjects were divided into a control group, a conventionally trained group, and a resistance trained group. The control group participated in curricular and extracurricular activities, but were not a part of any organized sports team. The conventionally trained group

Table 1. H:Q strength ratio measurements in youth soccer players

Reciprocal muscle group ratios (rad/s)	Controls		Conventionally trained soccer players		Resistance-trained soccer players	
	Dominant	Non-dominant	Dominant	Non-dominant	Dominant	Non-dominant
$H_{ECC}:Q_{CON}$ ratio						
1.08	0.71 ± 0.07	0.70 ± 0.10	0.68 ± 0.12	0.65 ± 0.09	0.70 ± 0.09	0.71 ± 0.12
4.32	1.10 ± 0.22	1.06 ± 0.15*	0.91 ± 0.10	0.89 ± 0.09	1.04 ± 0.12	1.05 ± 0.19†
$H_{CON}:Q_{ECC}$ ratio						
1.08	0.45 ± 0.10	0.42 ± 0.08	0.44 ± 0.06	0.43 ± 0.07	0.50 ± 0.09	0.49 ± 0.07
4.32	0.30 ± 0.08	0.28 ± 0.07*	0.36 ± 0.06	0.33 ± 0.05	0.34 ± 0.07	0.32 ± 0.08†

*Significant differences between the conventionally trained soccer players and the controls.
†Significant differences between conventionally trained soccer players and the resistance-trained soccer players.

participated in three to four hours of practice and one match per week. Their training sessions were exclusively focused on the development of tactical and technical soccer skills. The third group did the same training as the conventional group with an addition two sessions of resistance training on the lower extremities per week. Each group consisted of fifteen boys. This study used similar tests as the Evangelidis study to measure the peak maximal torque of the quadriceps and hamstrings in each leg.

Their initial findings indicated that muscle load patterns experienced during soccer may have a negative impact on the balance of muscle strength between the quadriceps and hamstrings as seen in Table 1. In addition, the results also indicate the possibility of correction through muscle-specific resistance training. The changes in H:Q ratios were insignificant at low velocity knee flexion trials, but were significant at higher velocities. The low functional ratios at high velocity in conventionally trained soccer players imply that the traditional muscle loads experienced while playing soccer favor the development of quadriceps dominance. However, functional ratios significantly increased in the resistance trained group. The change was due to a significant improvement in the eccentric strength of the hamstrings, thus increasing the H:Q ratio. The H:Q ratios between the controls and the resistance trained groups showed no significant differences, indicating that resistance training does not increase joint stabilization from the control, but rather opposes the effects of sport specific training and repetitive muscle loads. The strengths of this study included a sample size large enough to yield a 0.05 α level, which is large enough to yield results with 80% power. In addition, the investigators measured both dominant and non-dominant legs, allowing for bilateral comparison of muscle development. However, the study failed to measure values throughout the whole range of motion, although they did measure values at the injury-significant angles of knee extension. Overall, the study provides insight on the possible effects of sport-specific repetitive muscle loads on developing muscle. (Iga)

Table 2. Top Ten Injuries in Major and Minor League Baseball by Injury Type and Body Part

	Major League		Minor League	
Injury Diagnosis	No.	%	No.	%
Hamstring strain	50	5.7	218	5.9
Adductor groin strain	36	4.1	85	2.3
Oblique muscle strain	36	4.1	88	2.4
Hand contusion	32	3.7	203	5.5
Leg contusion	26	3.0	124	3.4
Knee contusion	26	3.0	88	2.4
Quadriceps strain	25	2.9		
Foot contusion	22	2.5	104	2.8
Concussion	18	2.1	101	2.7
Paralumbar muscle strain	18	2.1		
Other shoulder injury			78	2.1
Elbow contusion			73	2.0

[a]Frequencies are given in descending order by major league. Empty cells indicate an injury occurrence did not reach the top 10 in that league.

While similar, the differences between the studies are significant enough to lead to opposing results. The age groups and experience of the athletes varied between the studies, with the Iga study focusing on youth athletes and the Evangelidis study focusing on college athletes. In addition, the different muscle requirements of football and soccer may have had an effect on the outcomes. Soccer requires endurance over long periods of time, likely leading to the recruitment of type I slow twitch muscle fibers specialized in oxidation. Conversely, football requires short bursts of energy, with the average play lasting about eight seconds. This means the muscles are likely to recruit more type II fast twitch muscle fibers. The effects of muscle fiber types on asymmetric whole-muscle development has not been extensively explored. Finally, the Evangelidis study tested football players which participated in strength training in addition to their technical football training. As shown in Iga's study, strength training may have had a reversing effect on the development of asymmetric muscle and assisted in the development of eccentric hamstring strength. Ultimately, the effect of sport-specific training on cross-joint muscular development remains unclear. Muscle development is difficult to test and analyze accurately due to the highly variant nature of gene expression and protein metabolism amongst different individuals. One's predisposition for asymmetrical muscle development may be more affected by their DNA than any quantifiable lifestyle choices.

Cross-Joint Asymmetry and Injury Risk

Injury Occurrence in the NFL and MLB

Injuries that occur in professional sports are well documented by each league's injury surveillance systems. Major League Baseball conducted a single season study in 2011 to assess the current rate of injury relative to athlete exposures. As shown in Table 2, they found that the thigh was the most injured region of the body, accounting for 15.5% of all injuries. In addition, hamstring strains had a high incidence of re-injury, as calculated from injuries recorded in the 2010 season. Analysis of the MLB injury surveillance system yielded a re-injury rate of 20% in the hamstrings (Ahmad). The recurrence of injury may be attributed to the further loss of eccentric hamstring strength after initial injury and failure to rebuild hamstring strenght prior to return to play. This would support the theory that lower extremity muscular imbalance is an attributing factor in the high incidence of hamstring injury. Further analysis of MLB injury data yielded a pattern in time of injury. In both the major and minor leagues, the injury rate is at a peak at the beginning and end of the season, as seen in Table 3. Reasons for the pattern could include poor conditioning at the beginning of the year and fatigue at the end of the season. The study, however, had its limitation due to the single-year nature of the review. Medical history of players was neglected in the analysis of injury rate and there is no longitudinal data to support findings over time. Return to play time and re-injury risk also lose accuracy due to differences in individual players and variability in the medical support provided for treatment. Nevertheless, tha data is an indicator that hamstring injury prevention should be a focus in preseason programs.

Table 3. Hamstring injury occurrence by month, Major and Minor Leagues, 2011

	No. (% of Total)	Total No. of Games	Injury Rate (1 Hamstring Injury Every *n* Games)	Average Temperature, °F
Major league[a]				
April	6 (12)	392	65	63
May	13 (27)	420	32	68
June	6 (12)	400	67	75
July	8 (16)	395	49	82
August	3 (6)	420	140	78
September	3 (6)	117	39	72
Minor league[b]				
April	33 (15)	1370	42	
May	44 (20)	1892	43	
June	28 (13)	2506	89	
July	45 (21)	3161	70	
August	41 (19)	2855	70	
September	7 (3)	322	46	

[a]This analysis excludes 11 hamstring injuries that occurred in spring training or postseason games.
[b]This analysis excludes 20 hamstring injuries that occurred in spring training or postseason games

The NFL conducted a similar study to analyze data collected from their injury surveillance system between 1989 and 1998. In that time, the league recorded 1716 hamstring injuries, with the rate per season varying between 160 and 210. In total, 16.5% of all hamstring injuries were re-injuries, with the rate being closer to that of the MLB when the preseason was excluded (19.7%). The results coincide with the MLB analysis in that a single hamstring injury will likely increase the possibility of another hamstring injury to the same athlete.

Table 4. Injury by Time of Year and Session Type

	Injuries	Exposures	IR/1000 A-E
Preseason			
Game	199	80 691	2.47
Practice	713	872 202	0.82
Regular season			
Game	603	206 696	2.92
Practice	182	999 999	0.18

[a]A-E, athlete-exposure; IR, injury rate.

Like the MLB, the NFL also did an analysis on the time of year that each injury occurred. The NFL added an extra dimension by recording if the injury occurred during practice or a game. The results of the NFL's study is shown in table 4. The rate of incidence was significantly higher in preseason practices than during the regular season. In fact, data analysis showed that 53.1% of hamstring injuries occurred in the seven-week preseason. More than 70% of preseason injuries occurred in July, the first month of participation for the season. August, the first month of preseason games, also has the highest rate of injury at

23.7% of total game injuries (Elliot). The results of the NFL study confirm that of the MLB study. Players are subject to a much higher potential for injury in the early parts of their season than in the late season games and practices. A number of factors contribute to the high injury incidence in the preseason, the strongest of which is the deconditioning of athletes upon starting training. Players enter preseason workouts with an imbalance of quadriceps to hamstring ratio, causing the joint to favor the quadriceps attachment sites. Without proper strengthening of the hamstrings, fast twitch eccentric contractions will cause strains and stretching of the hamstring muscle beyond normal parameters to adjust for the favoring of the joint towards the quadriceps side. Nevertheless, other factors such as fatigue and player demographics play a role in injury risk as well.

The Fatigue Factor

An important factor in hamstring and knee injuries is that imbalanced conditioning of the quadriceps and hamstrings will lead to more fatigue in the hamstrings overtime, presenting an increased risk of muscle strains or knee sprains. A 2014 study by Robert Timmins tested the fatigue factor of hamstring muscles by measuring their myoelectrical activity. Seventeen recreationally active men with no history of lower extremity injury took part in sprint testing and then had myoelectric activity to the biceps femoris tested for signs of fatigue or induced weakness. Normalized bicep femoris myoelectrical activity was

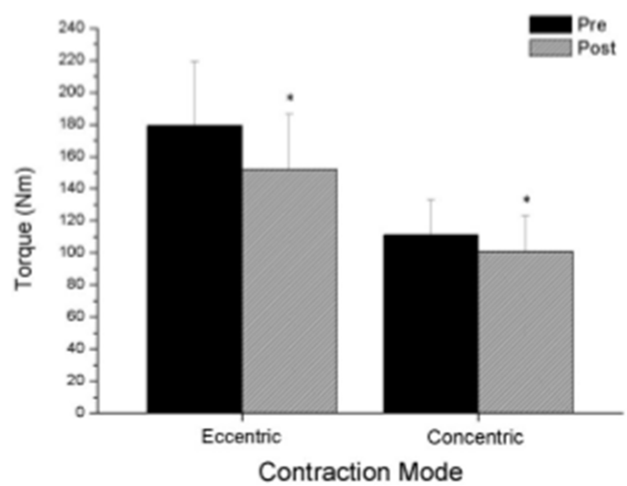


Figure 4. Peak knee flexor torque at isokinetic contraction modes before and after a sprinting session. Error bars illustrate SD. P<0.05 pre vs. post

significantly reduced by 10% after the sprint exercises. The reduction in myoelectrical activity was a likely cause of overall reduced knee flexor strength. In terms of strength, bicep femoris eccentric strength decreased by 15%, while the concentric strength decreased by 10% as shown in figure 4 (Timmins 2014). Since most hamstring injuries are non-contact injuries occurring while running or sprinting, it is appropriate to relate the decrease in bicep femoris activation with the fatigue, and therefore an increased injury risk. In terms of muscle asymmetry, stronger quadriceps muscles will fatigue more slowly during exercise than weaker hamstring muscles. This will cause the knee joint favor the quadriceps side and cause excessive hamstring stretching, thus enhancing poor joint balance caused by muscle asymmetry. This pattern of activation gives insight into the susceptibility of the hamstring towards injury during high speed running, and may help in injury screening and prevention.

Anterior Cruciate Ligament Tears

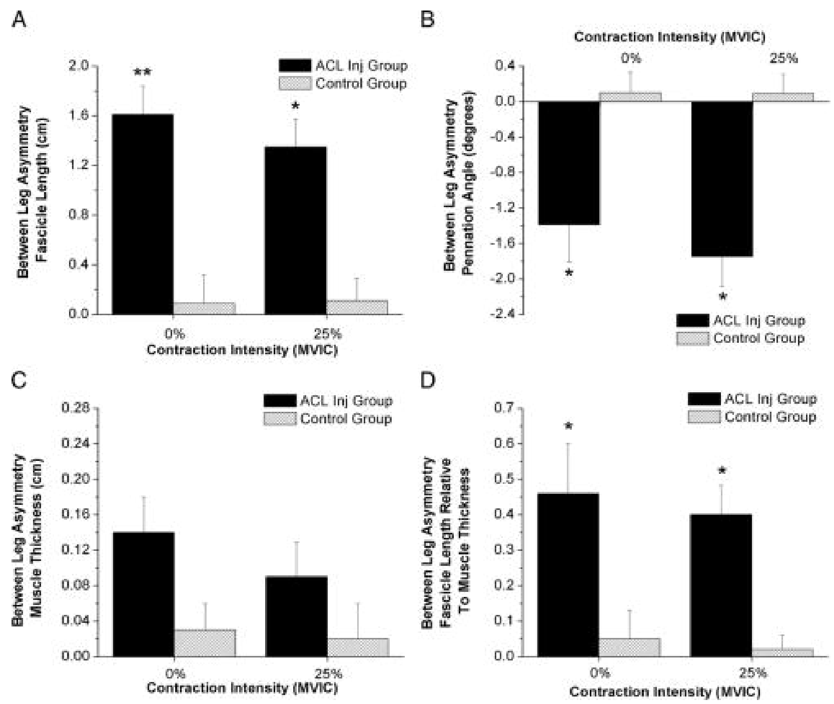


*Figure 5. Comparisons of between-leg asymmetry for the architectural characteristics of the BFlh in the group with previous ACL injury (uninjured minus injured-ACL Inj Group) with the absolute between-leg differences of the control group at both contraction intensities. A, Fascicle length. B, Pennation angle. C, Muscle thickness. D, Fascicle length relative to muscle thickness. Error bars illustrate the SD. *P < 0.05 injured vs control. **P < 0.001 injured vs control*

Each year, 53 ACL injuries occur in the NFL, meaning that each coach can expect one to two of their players to have their season ended by ACL injury (Olson). The effect of ACL injuries have been previously studied, finding that 80% of players suffering these injuries returned to play. On average, athletes returned to the field 10.8 months after surgical reconstruction. However, on field performance decreased by one-third based on statistical parameters, though statistics may not be indicative of full quality of play.

Risk factors for ACL injury are unclear, but studies have shown that hamstring strength and the risk of ACL tears are related. Timmins et al. observed the effects of ACL injury on hamstring strength and architecture of the bicep femoris. The study found a sharp decrease in muscle thickness and fascicle length after treatment (Timmins 2016). While the association may remain unclear, the evidence suggests that there is an association between hamstring development and ACL injuries. We cannot conclude that weak hamstrings may lead to ACL injuries from this data, but the association between muscle asymmetry and these ligament tears is worth investigating. Although speculative, one could theorize that the lower levels of eccentric strength in limbs with ACL injury history might be caused by a maladaptive tension limiting mechanism. Eccentric contractions cause more strain on the musculoskeletal structure of the knee than isometric contractions in the same way that lower levels of hamstring force act to reduce tissue loading in ACL-injured limbs. This suggests a strong connection between the eccentric force of hamstring contraction and the tissue load experienced by the ACL. The same can be said for the concentric force of quadriceps contraction, making balance between the two forces essential for ACL stability. When the forces produced are unbalanced due to muscle asymmetry, the ACL is at a higher risk of damage.

Lower Extremity Injury Screening and Prevention

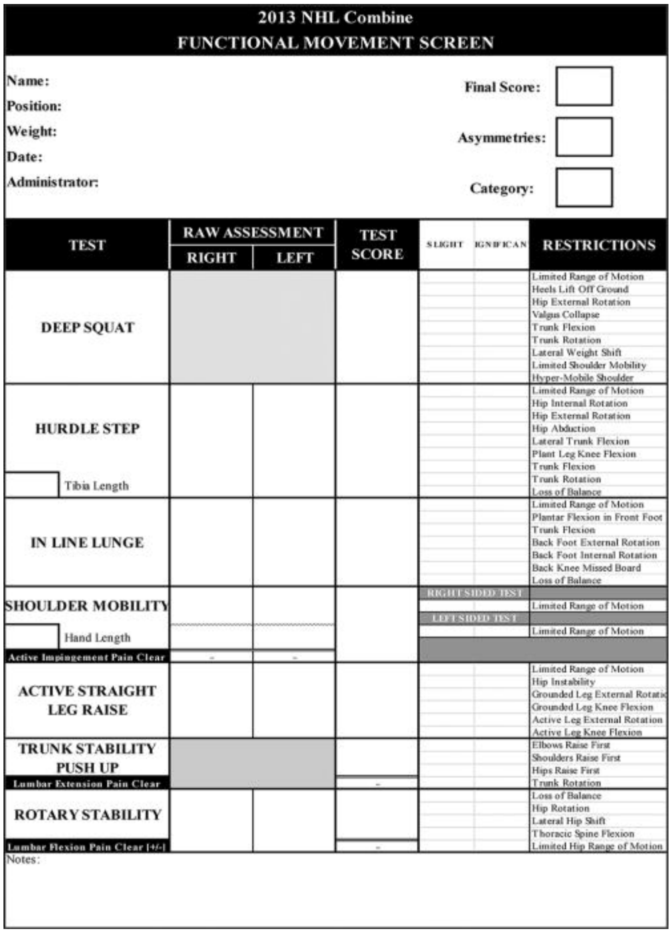
Injury Screening

Coaches, owners, and fans of professional sports teams relish the idea of predicting future injuries, especially serious injuries such as ACL tears, for prospective athletes before they enter the league. Teams exhaust all possible sources in incorporating drug screening, physicals, and MRIs in the draft. In fact, many player trades and transactions are contingent upon physicals done by team physicians. Researchers have thoroughly tested screening tools looking for techniques with the highest possible accuracy for identifying high injury risk. Dallinga et al. reviewed many of the common methods and their effectiveness for different injuries.

There is significant evidence that support multiple screening tools for ACL injuries, although some tests are more specific to certain sports. Side-to-side differences in tibiofemoral translation proved to be an accurate test for female basketball and soccer players. The same athletes were assessed for knee and hip joint flexion-extension and adduction-abduction on drop vertical jump task. The test has been coined the Landing Error Scoring System (LESS) and is based on the knee-abduction moment. In ACL-injured athletes, the abduction moment was 2.5 fold greater than healthy athletes. The knee abduction moment predisposed ACL injuries with 73% specificity and 78% sensitivity (Dallinga). A universal test for ACL tear predisposition was the extent of knee hyperextension. The study concluded that athletes with larger hyperextension angles were at a higher risk for ACL injuries. While these methods are reliable, they cannot predict risk of injury with 100% accuracy. No single ACL test could be found for soccer, rugby, and other running sports.

Hamstring injury assessments were performed on Australian football players focusing on several different factors. Several tests measured the flexibility of the hamstrings using tests such as the sit-and-reach, active knee extension and passive straight leg raise. While flexibility was determined to be a valid screening test for football players, the same tests proved ineffective for soccer players. Athlete age was a major screening factor as investigators found that athlete over age 23 were more susceptible to hamstring injury. One study found that the H:Q ratio was a significant predictor of hamstring strain in Australian football players. The data yielded a 95% confidence interval, suggesting that the H:Q ratio might be a screening test worth further investigation (Dallinga).

Application of Injury Screening: The NHL



2013 NHL Combine
FUNCTIONAL MOVEMENT SCREEN

Name:
Position:
Weight:
Date:
Administrator:

Final Score:
Asymmetries:
Category:

TEST	RAW ASSESSMENT RIGHT	RAW ASSESSMENT LEFT	TEST SCORE	SLIGHT	IGNIFICAN	RESTRICTIONS
DEEP SQUAT						Limited Range of Motion Heels Lift Off Ground Hip External Rotation Valgus Collapse Trunk Flexion Trunk Rotation Lateral Weight Shift Limited Shoulder Mobility Hyper-Mobile Shoulder
HURDLE STEP Tibia Length						Limited Range of Motion Hip Internal Rotation Hip External Rotation Hip Abduction Lateral Trunk Flexion Plant Leg Knee Flexion Trunk Flexion Trunk Rotation Loss of Balance
IN LINE LUNGE						Limited Range of Motion Plantar Flexion in Front Foot Trunk Flexion Back Foot External Rotation Back Foot Internal Rotation Back Knee Missed Board Loss of Balance
SHOULDER MOBILITY Hand Length				RIGHT SIDED TEST		Limited Range of Motion
				LEFT SIDED TEST		Limited Range of Motion
Active Impingement Pain Clear	-	-				
ACTIVE STRAIGHT LEG RAISE						Limited Range of Motion Hip Instability Grounded Leg External Rotatio Grounded Leg Knee Flexion Active Leg External Rotation Active Leg Knee Flexion
TRUNK STABILITY PUSH UP						Elbows Raise First Shoulders Raise First Hips Raise First
Lumbar Extension Pain Clear			-			Trunk Rotation
ROTARY STABILITY						Loss of Balance Hip Rotation Lateral Hip Shift Thoracic Spine Flexion
Lumbar Flexion Pain Clear [+/-]			-			Limited Hip Range of Motion

Notes:

Figure 6. FMS form used at the 2013 NHL Combine

Every offseason, the NHL hosts over one hundred young athletes at their Draft Combine. There, participants are subject to rigorous medical examination including medical history, a physical, orthopedic examination, electrocardiogram, and motor coordination. In 2013, the draft added another screen to predict musculoskeletal injury risk called the Functional Movement Screen (FMS). The test consists of seven different movements scored on a scale of 0-3 (Rowan). The screening identifies deficiencies in fundamental movement patterns and asymmetries that occur during these movements. The results of an FMS can be used to predict injury risk before entering athletic competition or being drafted to a team. The NHL is the first of the Big 4 to institute the use of a test for musculoskeletal predispositions for injury. They are sure not to be the last, however, as FMS will become more useful as injuries become more prevalent and player contracts become lucrative.

Injury Prevention

The primary prevention method for hamstring and knee injuries should be the maintenance of muscular balance across the knee joint. More often than not, this means a lifting or resistance program designed to strengthen the hamstring muscle group. Nevertheless, there is debate about the effectiveness of eccentric hamstring strengthening in the prevention of hamstring strains and knee sprains. Goode et al. reviewed the findings of four studies claiming that eccentric hamstring strengthening was ineffective in preventing future hamstring injury. The review found that compliance had a major effect on end results and greatly skewed data toward null results. When compliant subjects were assessed individually, the findings indicated that eccentric hamstring strengthening had a significant effect of hamstring injury prevention. Ultimately, there is significant evidence to prove that simple eccentric hamstring strengthening can prevent strains in athletes (Goode). While a focus on the hamstrings is important, maintaining a balance work out plan and ensuring symmetrical cross-joint development would also be effective in reducing inherent injury risk.

Conclusion

Studies done on hamstring strains are repeatedly indicating that hamstring and quadriceps asymmetry might play a major role in injury risk. While we cannot conclusively state that sport-specific training is responsible for disproportional quadriceps dominance, we do have a blueprint for preventing hamstring and knee injuries. In some sports, training may not be required to counteract the natural effects of sport-specific training, but balanced workouts can still be implemented to help in the prevention of muscle strains and knee ligament tears. With the high rate that hamstrings are being torn in sports, this strategy is a powerful tool in improving the performance and longevity of elite athletes. The institution of regular balanced workouts will not only benefit the athletes, but also team owners, coaches, and fans who will have the opportunity to watch spectacular athletes perform at their highest level for long periods of time.

References

Ahmad CS, Dick RW, Snell E, Kenney ND, Curriero FC, et al. Major and Minor League Baseball Hamstring Injuries: Epidemiologic Findings From the Major League Baseball Injury Surveillance System. Am J Sports Med. 2014 Jun;42(6):1464-70. PubMed PMID: 24727933.

Bradley J, Honkamp NJ, Jost P, West R, Norwig J, et al. Incidence and variance of knee injuries in elite college football players. Am J Orthop (Belle Mead NJ). 2008 Jun;37(6):310-4. PubMed PMID: 18716695.

Brophy RH, Wright RW, Powell JW, Matava MJ. Injuries to kickers in American football: the National Football League experience. Am J Sports Med. 2010 Jun;38(6):1166-73. PubMed PMID: 20197495.

Brughelli M, Morin JB, Mendiguchia J. Asymmetry after Hamstring Injury in English Premier League: Issue Resolved, Or Perhaps Not?. Int J Sports Med. 2015 Jun;36(7):603. PubMed PMID: 26076012.

Dallinga JM, Benjaminse A, Lemmink KA. Which screening tools can predict injury to the lower extremities in team sports?: a systematic review. Sports Med. 2012 Sep 1;42(9):791-815. PubMed PMID: 22909185.

Dengel DR, Bosch TA, Burruss TP, Fielding KA, Engel BE, et al. Body composition and bone mineral density of national football league players. J Strength Cond Res. 2014 Jan;28(1):1-6. PubMed PMID: 24149760.

Elliott MC, Zarins B, Powell JW, Kenyon CD. Hamstring muscle strains in professional football players: a 10-year review. Am J Sports Med. 2011 Apr;39(4):843-50. PubMed PMID: 21335347.

Enoka RM. Neuromechanical Basis of Kinesiology. 2 ed. Frey R, Galasyn-Wright L, editors. Champaign, IL: Human Kinetics; 1994. 465p.

Evangelidis PE, Pain MT, Folland J. Angle-specific hamstring-to-quadriceps ratio: a comparison of football players and recreationally active males. J Sports Sci. 2015;33(3):309-19. PubMed PMID: 25073098.

Goode AP, Reiman MP, Harris L, DeLisa L, Kauffman A, et al. Eccentric training for prevention of hamstring injuries may depend on intervention compliance: a systematic review and meta-analysis. Br J Sports Med. 2015 Mar;49(6):349-56. PubMed PMID: 25227125.

Hägglund M, Waldén M, Ekstrand J. Risk factors for lower extremity muscle injury in professional soccer: the UEFA Injury Study. Am J Sports Med. 2013 Feb;41(2):327-35. PubMed PMID: 23263293.

Hickey KC, Quatman CE, Myer GD, Ford KR, Brosky JA, et al. Methodological report: dynamic field tests used in an NFL combine setting to identify lower-extremity functional asymmetries. J Strength Cond Res. 2009 Dec;23(9):2500-6. PubMed PMID: 19910824; NIHMSID: NIHMS435170; PubMed Central PMCID: PMC3561669.

Hirshorn KC, Cates T, Gillogly S. Magnetic resonance imaging-documented chondral injuries about the knee in college football players: 3-year National Football League Combine data. Arthroscopy. 2010 Sep;26(9):1237-40. PubMed PMID: 20630691.

Iga J, George K, Lees A, Reilly T. Cross-sectional investigation of indices of isokinetic leg strength in youth soccer players and untrained individuals. Scand J Med Sci Sports. 2009 Oct;19(5):714-9. PubMed PMID: 18627555.

Kerr ZY, Dompier TP. NCAA Injury Surveillance Program. Indianapolis, IN: Datalys Center; 2013. 4 Fact Sheets. Available from: http://www.datalyscenter.org/fact-sheets/.

Lempainen L, Sarimo J, Mattila K, Heikkilä J, Orava S, et al. Distal tears of the hamstring muscles: review of the literature and our results of surgical treatment. Br J Sports Med. 2007 Feb;41(2):80-3; discussion 83. PubMed PMID: 17138628; PubMed Central PMCID: PMC2658938.

Malliaropoulos NG. Non contact Hamstring injuries in sports. Muscles Ligaments Tendons J. 2012 Oct;2(4):309-11. PubMed PMID: 23738316; PubMed Central PMCID: PMC3666535.

Olson D, Sikka RS, Labounty A, Christensen T. Injuries in professional football: current concepts. Curr Sports Med Rep. 2013 Nov-Dec;12(6):381-90. PubMed PMID: 24225523.

Pérez-Bellmunt A, Miguel-Pérez M, Brugué MB, Cabús JB, Casals M, et al. An anatomical and histological study of the structures surrounding the proximal attachment of the hamstring muscles. Man Ther. 2015 Jun;20(3):445-50. PubMed PMID: 25515332.

Rowan CP, Kuropkat C, Gumieniak RJ, Gledhill N, Jamnik VK. Integration of the functional movement screen into the National Hockey League Combine. J Strength Cond Res. 2015 May;29(5):1163-71. PubMed PMID: 25719918.

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 Dec;48(22):1599-606. PubMed PMID: 25388959; PubMed Central PMCID: PMC4267196.

Söderman K, Alfredson H, Pietilä T, Werner S. Risk factors for leg injuries in female soccer players: a prospective investigation during one out-door season. Knee Surg Sports Traumatol Arthrosc. 2001 Sep;9(5):313-21. PubMed PMID: 11685365.

Timmins RG, Bourne MN, Shield AJ, Williams MD, Lorenzen C, et al. Biceps Femoris Architecture and Strength in Athletes with a Previous Anterior Cruciate Ligament Reconstruction. Med Sci Sports Exerc. 2016 Mar;48(3):337-45. PubMed PMID: 26429732.

Timmins RG, Opar DA, Williams MD, Schache AG, Dear NM, et al. Reduced biceps femoris myoelectrical activity influences eccentric knee flexor weakness after repeat sprint running. Scand J Med Sci Sports. 2014 Aug;24(4):e299-305. PubMed PMID: 24422638.