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ANTERIOR CRUCIATE LIGAMENT PREVENTION: EFFECT OF
NEUROMUSCULAR TRAINING COMPLIANCE ON MUSCULAR
STRENGTH DEVELOPMENT

DISSERTATION

A dissertation submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in the College of Health Sciences
at the University of Kentucky

By

Daisuke Sugimoto
Lexington, Kentucky

Co-Directors: Dr. Carl G. Mattacola, Full Professor of Athletic Training
and Dr. Timothy E. Hewett, Adjunct Professor of Athletic Training
Lexington, Kentucky

2013

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ABSTRACT OF DISSERTATION

ANTERIOR CRUCIATE LIGAMENT PREVENTION: EFFECT OF NEUROMUSCULAR TRAINING COMPLIANCE ON MUSCULAR STRENGTH DEVELOPMENT

The anterior cruciate ligament (ACL) originates from posterior part of the medial side of the lateral condyle of femur to anterior intercondylar notch between a transverse meniscal ligament and medial side of medial meniscus of tibia. Once ACL is disrupted, pain, effusion and atrophy are commonly observable and cause functional disability. Because of the functional limitations, athletic participation is severely restricted. ACL injury is more prevalent in physically active females compared to their male counterparts in the sports of basketball and soccer in high school and collegiate levels.

Several attributes of females are considered risk factors for the higher ACL injury incidences and include: anatomy, physiology and neuromuscular/biomechanics. Among them, neuromuscular/biomechanics is the only modifiable risk factor. Performing neuromuscular training may change muscular strength profiles, which may lead to reduction in ACL injury incidence in female athletes. However, this principle was not fully examined. Also, neuromuscular compliance may play a role in muscular strength development and ACL injury incidences.

Thus, the purpose of this dissertation was to investigate the effects of neuromuscular training compliance on muscular strength development and ACL injury incidence. The influence of hip abductor, hamstrings and quadriceps strength was examined in this project.

The results of these studies indicate neuromuscular training is an effective intervention to reduce ACL injury incidence in female athletes, and there is an inverse dose-response relationship between compliance of the neuromuscular training and number of ACL incidences in female athletes. The effect of compliance on muscular strength development was inconsistent. The results of these studies support that compliance of neuromuscular training is a key to reduce ACL injury incidences; however, more studies are need to conclude neuromuscular training compliance effects on muscular strength development in female athletes.

KEYWORDS: ACL injury, neuromuscular training, compliance, muscular strength development, female athletes.

Dai Sugimoto
Student's Signature

May 20, 2013
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ANTERIOR CRUCIATE LIGAMENT PREVENTION: EFFECTS OF
NEUROMUSCULAR TRAINING COMPLIANCE ON MUSCULAR
STRENGTH DEVELOPMENT

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Chapter 1 Introduction

Background

The knee is one of the most frequently injured joint in college athletics. According to 16 years of 15 NCAA sports' epidemiology data, approximately 54% of all injuries are lower extremity, which is the highest compared other body parts.⁶⁴ Although the rate was not stated, the author stated that the lower extremity injuries were “mostly consists of knee and ankle joints”.⁶⁴ The high prevalence of knee injuries may stem from structures that stabilize the joint alignment. Therefore, structures of the knee joint anatomy need to be discussed, especially static and dynamic structures that enhance stabilizing knee joint.

An anterior cruciate ligament (ACL) plays an integral role for a knee joint stability. Once an individual tears an ACL, the individual immediately experiences various functional difficulties as well as severe pain and joint effusion. In athletic setting, because of the functional difficulties, most ACL injured athletes were forced to limit their physical activities and restrict their athletic participations, and rate of the time loss is the longest compared to ankle and traumatic head injuries.⁶⁴ In order to restore the torn ACL, it has been reported that approximately 350,000 ACL reconstruction surgeries are performed in the US.¹⁶¹ After ACL reconstruction surgery and rehabilitation, the newly grafted ACL provides stability on knee joint, and most people are able to return to their desired physical activities.^{19, 144} Adequate knee stability is a key for returning to a physically active lifestyle because it allows the knee joint to have more dynamic control without episodes of giving out. It is theorized that ACL plays a role as a functional stabilizer of the knee joint from architectural, mechanical, and sensorimotor standpoints.

An estimated number of ACL injuries ranged from 80,000 to 350,000 annually in the US.^{19, 161} Along with the number of people who suffer the ACL injuries, a few investigators and research teams examined how ACL injury occurs. Based on their reports, several common ACL injury mechanisms have been emerged.^{1, 57} Identifying the mechanism of ACL injury is important because it gives a first step to develop an effective preventive intervention strategy. Hence, the purpose of this project is to describe common pathomechanics of ACL injury and also identify distribution of the common ACL pathomechanics based on sexes.

Static Stabilizers

Bony Contribution

The knee joint consists of three bones: femur, patella, and tibia. The femur is the longest bone in the human body,^{44, 92} and distal end of the femur has medial and lateral condyles. Area between the medial and lateral condyles of the femur is called intercondylar fossa. On anterior side of the intercondylar fossa, which has concave and smooth area is called patellar surface. The patella articulates to the patellar surface, and the patella and patellar surface form a femoropatellar or often referred to patellofemoral joint.^{44, 92} The medial and lateral condyles articulate to the proximal tibia bone, which compose a tibiofemoral joint. The knee joint is often referred as a hinge joint with rotation because tibiofemoral joint makes the knee joint flex and extend like a hinge and also accompanies a tibial rotational component.

Cartilaginous Contribution

Between the tibiofemoral joint, there is a cartilaginous structure called menisci. The menisci consist of medial and lateral meniscus.^{44, 92} The medial meniscus looks like a C shape,

and attaches to medial collateral ligament (MCL). On the other hand, the lateral meniscus appears like an O shape and smaller compared to the medial meniscus. Anteriorly, the medial and lateral meniscus are connected by a transverse meniscal ligament and provide thicker and more available surfaces to hold the medial and lateral condyles of the femur.^{44, 92} Because of the more available surface, weight bearing pressure can be distributed more evenly throughout the menisci; thus, the menisci function as a shock absorber. Also, design of the menisci contributes rolling, gliding, and spinning motions of the knee joint.

Ligamentous Contribution

Many ligamentous structures surround the knee joint to enhance the joint stability. Two cruciate ligaments, anterior cruciate ligament (ACL) and posterior cruciate ligament (PCL), play a role to stabilize the tibiofemoral joint anteriorly and posteriorly. The ACL limits posterior rolling of the femoral condyles on the tibial and prevents anterior displacement of the tibia, which is often referred to hyperextension of the knee. On the other hand, the PCL holds anterior rolling of the femur on the tibial plateau and limits posterior displacement of the tibia, which helps preventing hyperflexion of the knee joint.^{44, 92}

Ligamentous structures that locate medial and lateral sides of the knee joint provide stability against force applied from side. MCL extends inferiorly from the medial epicondyle of femur to medial surface of tibia. Slightly posterior to the MCL, there is a posterior oblique ligament, which attaches to adductor tubercle of femur and distally inserts to posterior joint capsule and tibia.¹²³ On lateral side, lateral collateral ligament (LCL) runs from the lateral epicondyle of femur to the lateral surface of fibular head. Also, lateral joint capsule is located near the LCL, and arcuate popliteal ligament strengthens the knee joint stability posterolaterally.⁹²

Other Structural Contribution

External fibrous layer of capsule and internal synovial membrane builds a joint capsule. The external fibrous layer attaches to femoral condyles and intercondylar fossa superiorly and inferiorly encloses tibial plateau of tibia.^{44, 92} Anteriorly, a patella ligament (tendon) overlaps with the external fibrous layer. The internal synovial membrane lines with the external fibrous layer medially and laterally, but centrally, the internal synovial membrane covers the intercondylar fossa. Also, both cruciate ligaments attach right and left femorotibial articular cavity via posterior aspect of patella.^{44, 92}

Dynamic Stabilizers

Muscular Contribution

Several major muscle groups assist stabilizing the knee joint. Rectus femoris, vastus lateralis, vastus intermedius, vastus medialis, vastus medialis oblique, and articularis genu are considered as a quadriceps muscle group and provide dynamic stability anteriorly on knee joint. Distal tendons of the quadriceps except for articularis genu compose patellar ligament (tendon), which runs proximal to the patella to tibial tuberosity. The primary function of the quadriceps is to extend knee joint.^{44, 92}

Posteriorly, distal tendons of hamstrings muscle group, semitendinosus, semimembranosus, and biceps femoris, cover the knee joint medially and laterally. Medially, semitendinosus attaches to superior and medial part of tibia. Likewise, semimembranosus connects to posterior and medial condyle of tibia. Biceps femoris muscle has two distal tendons: long head and short head. Both long and short heads of the biceps femoris muscle insert to lateral side of fibular head. The main function of the hamstrings is knee flexion.^{44, 92}

Similar to the distal hamstring tendons, proximal gastrocnemius muscle tendons have medial and lateral attachments. Lateral head of the gastrocnemius muscle attaches lateral aspect of lateral femoral condyle, and medial head connects to popliteal surface of femur and superior to medial condyle. Plantaris is another muscle located to posterior side of lower leg and attaches to inferior end of lateral supracondylar line of femur and also oblique popliteal ligament, which comes from semimembranosus tendon, runs obliquely to intercondylar fossa to reinforce the posterior joint capsule.^{44, 92}

Medially, pes anserine muscles, sartorius, gracilis, and semitendinosus, insert to the superior part of medial surface of tibia. The pes anserine muscles were innervated by three different nerve groups (femoral nerve for sartorius, obturator nerve for gracilis, and tibial nerve for semitendinosus) and play a dynamic role as a medial rotator of lower leg. On the lateral side, tensor fascia latae via iliotibial tract attaches to lateral condyle of tibia, which often called Gerdy's tubercle. The tensor fascia latae functions abducting hip, rotating thigh medially, and maintaining pelvis level equally in weight-bearing activities.^{44, 92} Also, the biceps femoris, which attaches to head of fibula, and works as a lateral rotator of the lower leg.^{44, 92}

Another muscle that takes an important role as a dynamic stabilizer is popliteus. The popliteus originates from lateral surface of lateral condyle of femur and lateral meniscus and attaches to posterior and superior to soleal line of tibia. It is unique that the proximal end of the popliteus muscle is connected to posterior menisco-femoral ligament. In the final 20 degrees of the terminal knee extension, the tibia rotates externally since the medial femoral condyle is bigger than the lateral condyle and also the medial meniscus has longer anterior and posterior dimension to add stability in the knee extension motion. This phenomenon is called a screw-home mechanism.⁹⁰ The popliteus muscle takes an active role in the screw-home mechanism.

Conversely, when the knee is flexed from the terminal extension position, the popliteus muscle actively assists unscrewing (moving the externally rotated tibia to neutral alignment) the tibia with knee flexion motion.⁹⁰

ACL Anatomy and Roles

Architectural Design of ACL

An ACL is obliquely tilted approximately at 26.6 ± 6 degrees vertically and runs from posterior part of the medial side of the lateral condyle to anterior intercondylar area between a transverse meniscal ligament and medial side of medial meniscus are located¹²⁴ (Figure 1.1). The distal attachment of the ACL is sometimes referred as foot region¹⁰ (Figure 2.1). The ACL length is approximately 32-38 mm, and the ACL width is 10 mm¹²⁴ (Figure 3.1). The narrowest point is at the middle of the ACL fiber,⁴⁹ and the diameter was reported as 36 mm² and 44 mm² for females and males.⁷ The ACL consists of anetriomedial bundle (AMB), intermediate bundle, and posteriorlateral bundle (PLB)^{6, 28, 30, 31, 150} (Figure 4.1).

In knee flexion motion, the AMB tightens, and the PLB loosens.¹⁶⁶ On the other hand, in knee extension motion, the AMB moderately loosens, and PLB is tight.¹⁶⁶ However, both AMB and PMB elongate in final 30 degrees of knee extension.⁶ The elongation of the AMB and PMB in final 30 degrees of knee extension occurs because the ACL predominantly functions restricting anterior displacement of tibia.²⁷ When tibia is internally rotated, the AMB and PMB tend to lengthen more than tibial external rotation, and this phenomenon is more noticeable in 30 degrees of knee flexion.⁶

ACL Mechanical Stability

The ACL predominantly provides the knee joint stability for restricting anterior tibial displacement. Although the AMB and PMB are slightly movable with knee motions (flexion, extension, and rotation), inside of lateral condyle where the AMB and PMB originate has an isometric area.^{6, 138} From the isometric area in lateral condyle to the anterior intercondylar area where the ACL inserts distally, the ACL provides a mechanical stability. A maximum tolerable stress created by a metal machine called tensile load for the ACL is reported as 2160 ± 157 Newton.¹⁶²

The distal femur has a convex appearance, and the proximal tibia has the concave shape. Because of the convex and concave articulation between the distal femur and proximal tibia, rolling, gliding, and spinning motions occur in dynamic knee motions. ACL is theorized to provide mechanical stability anterior and posterior rolling and gliding motions in conjunction with posterior cruciate ligament (PCL). In addition to the anterior and posterior stability, the ACL and PCL is believed to supply side by side (valgus and varus) stability with rotation.¹²⁹

ACL Sensorimotor Function

Approximately 1.0-2.5% of the ACL tissue properties consist of neural elements.^{134, 135} More specifically, the neural elements of the human ACL consist of pacinian corpuscles, ruffini corpuscles, and golgi tendon organ (GTO)-like receptor.² The pacinian corpuscles are specialized to detect sudden perturbation, acceleration, or deceleration by low stimuli such as vibration and pressure.¹⁴³ On the other hand, the ruffini corpuscles function to adapt slow movements in tissue stress and strain and are designed to detect joint angle, velocity, and pressure changes.¹⁴³ The GTO-like receptor has a high threshold to mechanical pressure and compression and is capable of sending signals for relatively prolonged times.¹⁴³ In short, these mechanoreceptors are able to identify position, velocity, pressure, and pain associated with motions.¹⁴³

Once these mechanoreceptors detect internal and external perturbation, first order neurons transmit a signal to dorsal horn of spinal cord via dorsal root ganglia.¹³⁷ In the dorsal horn of spinal cord, the signal is carried toward thalamus by a dorsal column-medial lemniscus (DCML) pathway in spinal cord by second order neurons.¹³⁷ From the thalamus, third order neurons passed the signal to somatosensory cortex via thalamocortical tract. Finally, the signals are passed by other higher brain centers including cortex, motor cortex, basal ganglia, and cerebellum.¹³⁰

Once the signal is completely circulated in the brain, first order neurons, located in motor cortex, initiates relaying the signal to corticospinal tract.¹³⁷ The corticospinal tract continues passing the motor signal through ventral horn of spinal cord via second order neurons. The motor signal is passed to gamma motor neurons, which is specialized to provide accurate proprioceptive information through muscle spindles.¹³⁷

Since the ACL fibers contain mechanoreceptors, individuals with ACL tear often experience deficits in detecting passive joint motions or repositioning sense.^{96, 130} This phenomenon occurs because of a lack of sensory detection system. Without sensory feedback, it is extremely challenging to accurately locate the joint to original position.

ACL Tear and Knee Joint Stability

Once an ACL is torn, the knee joint starts demonstrating instability, which is believed in stemming from a lack of both mechanical and sensorimotor control. When an ACL is torn, a main mechanical stabilizer that prevents anterior tibial displacement is lacking. Because of a loss of the mechanical stabilizer, the knee joint will have excessive rolling and gliding motions in dynamic movements. Moreover, the ACL and PCL are considered to supply a side-to-side

stability with rotation secondary to the MCL and LCL.¹²⁹ Therefore, arthrokinematic spinning motion of the knee joint may be more apparent with individuals with torn ACL.

In addition to the loss of mechanical stability, the torn ACL is incapable of supplying the sensory feedback to higher centers of brain because of the inability of mechanoreceptors in the ACL. In fact, a few studies reported reduced abilities to detect passive joint motion or repositioning sense in ACL deficient and ACL reconstructed individuals.^{74, 96, 130} One study reported a negative correlation between the total number of mechanoreceptors and inaccuracy of joint position sense ($r = -0.41$).²

Because of the mechanical and sensory instability, individuals with ACL tear usually experience an episode of giving out in deceleration, cutting, pivoting, and landing movements. If the ACL is untreated, menisci usually resulted in developing tears over times because of the extreme rolling, gliding, and spinning motions created by excessive translation between femur and tibia. Although the ACL is reconstructed, risk of pre-mature osteoarthritis is higher than those who did not suffer ACL injury.^{79, 80} This phenomenon may be explained by that newly grafted ACL can provide a mechanical stability, but capabilities of the mechanoreceptors in the newly grafted ACL may not be same as the original ACL.

ACL Injury Pathomechanics Classifications and Distributions

Recent ACL research conference¹ supported a pathomechanic definition introduced by Hewett et al.⁵⁷ According to the definition, ACL injuries can be classified into three different schemes based on a type of contact mechanisms: Type I: Direct contact (external force was directly applied to injured knee and was probably the proximate cause of injury), type II: Indirect contact (external force was applied to athlete but not directly to the injured knee. The force was involved in the injury process but was probably not the proximate cause), and type III:

Noncontact (forces applied to the knee at the time of injury resulted from the athlete's own movements and did not involve contact with another athlete or object).⁵⁷ Previously published studies that investigated the pathomechanics of ACL injuries tried following the above classification schemes.^{3, 8, 13, 111, 156} However, they did not differentiate the direct and indirect contact ACL injuries.^{3, 8, 13, 111, 156} They simply combined the two mechanisms (direct and indirect mechanisms) and expressed it as a contact ACL injury.^{4, 8, 13, 111, 156}

Noncontact ACL Injury Mechanism

To understand underlying mechanism and risk factors for a noncontact ACL injury, numerous studies have been conducted. Using a prospective cohort study design, Hewett et al. discovered a few biomechanical differences between high school female athletes who suffered noncontact ACL injuries and those who did not.⁵⁹ The observed biomechanical differences were elevated knee abduction moment, limited knee flexion, excessive ground reaction force, and asymmetrical landing pattern in drop vertical jump. In addition to the knee kinematic difference, recent studies reported influence of trunk neuromuscular control on knee injury.^{59, 167} A three year prospective study that initially aimed to find trunk neuromuscular deficit and low back pain found a link between trunk control and ACL injury.¹⁶⁷ The study reported that ability to control a lateral trunk displacement accurately predicts future ACL injury. With a logistic regression model, trunk displacements, proprioception, and history of low back pain indicate future ACL injury risk with 91% accuracy in female, but not male, athletes.¹⁶⁷ Additionally, using NBA and WNBA players, a video analysis study reported that lateral trunk flexion and knee abduction angles were greater in cutting and landing tasks in female players who suffered ACL injuries compared to male and control female players.⁵⁹

Based on the available evidence, ACL tear is a resultant product of kinetic (neuromuscular) and kinematic (biomechanical) events in dynamic human movements. Followings are a potential sequence of a noncontact ACL injury mechanism: Upper body strength difference exists between males and females.^{34, 89} Because of the limited upper body strength, females may present more lateral displacement of trunk in cutting, pivoting, and landing activities. When the trunk is flexed laterally without sufficient control in the dynamic movements, weight can be shifted to one leg. If only one leg contacts on ground quicker than the other leg, ground reaction force (GRF) tends to be higher than both legs contacts since only one leg has to absorb the GRF. The GRF, as the result of asymmetrical movements, runs approximately lateral to center of femoral head, which produces external hip abductor torque. The Newton's third law states: For every action, there is an equal and opposite reaction. Thus, in order to balance the external hip abduction torque created by the lateral GRF, hip adductor is activated. The activated hip adductor musculature brings the thigh inwardly and potentially contributes to the hip adduction and internal rotation of femur. The increased hip adduction angles create increased knee abduction angles in weight-bearing activities.³⁸ As the results, the ACL is strained and occasionally torn if the external knee abduction moment is beyond the ACL's yielding point.

Indirect Contact ACL Injury Mechanism

A principle of the indirect contact ACL injury mechanism is the same as the noncontact ACL injury. In the noncontact mechanism, ACL bundles can be torn as a result of complex kinetic and kinematic events within dynamic human movements and without any contact. Conversely, in an indirect mechanism, an external force applied to body parts besides knee joint results in ACL tear. For instance, external force applied to trunk can create a loss of control on

the trunk, which is likely to generate excessive GRF because of the asymmetrical dynamic motions. Because the produced GRF runs laterally approximately to center of femoral head, external hip abductor torque is created. In order to compensate the torque, the hip adductor needs to be activated, which is likely to bring the knee joint in more abducted or valgus direction.

Another potential indirect contact ACL injury mechanism is a contact force on the thigh. During cutting, pivoting, and landing activities, if external force is applied from lateral side of thigh with fixed foot, the knee is forced to be moved toward an abducted direction, which can be resulted in an ACL tear. Similarly, if the external force comes from anterior side of the thigh, the knee is forced to be hyperextended. The hyperextended knee with a combination of anterior tibial translation and rotation¹²⁹ is likely to cause a strain on the ACL, which may cause an ACL tear.

Direct Contact ACL Injury Mechanism

A contact ACL injury is defined as an external force application to injured knee, which was probably the proximate cause of injury.⁵⁷ Several studies reported that external force application is likely to come from other players rather than balls, goals, or floors.^{4, 21} A recent descriptive laboratory study reported that an external force that induces knee abduction and anterior tibial translation increase the ACL strain by 4.6-fold.¹²⁹ Also, anterior tibial translation with internal and external rotations increase the ACL strain by 3.9-fold and 3.7-fold, respectively.¹²⁹ Therefore, direct external force applications to the knee joint, which cause knee abduction, anterior tibial translation with internal and external rotations are likely to elevate a risk to tear ACL with direct contact mechanism.

Distribution of ACL Injuries based on the Pathomechanics Classifications

Reviewing a five years of epidemiological data from the NCAA men's and women's soccer and basketball athletes, Arendt and Dick indicated that the most frequently observed ACL injury mechanism is noncontact.⁸ The study concluded 68.7% of all ACL injuries were noncontact in nature based on analysis of the injury mechanisms. However, the sex difference exists within the mechanisms. Although 55.4% of all ACL injuries were noncontact in nature in male athletes, 74.5% of all ACL injuries occurred with noncontact mechanism in female athletes. More specifically, the data can be organized by sex and sports. In a sport of soccer, number of contact and noncontact ACL injuries were about the same in males (34 contact vs. 32 noncontact ACL injuries), but females demonstrated 1.7 times higher noncontact mechanisms compared to contact mechanisms (31 contact vs. 53 noncontact ACL injuries). Similarly, in basketball, males had 1.9 times higher noncontact mechanisms relative to contact mechanisms (16 contact vs. 30 noncontact ACL injuries), whereas females suffered ACL injuries with noncontact mechanism with four times higher compared to ACL injuries with contact mechanism (34 contact vs. 137 noncontact ACL injuries).

Another study that analyzed the NCAA men's and women's soccer and basketball epidemiological data for a 13 years (1990-2002) generally supported the above findings.³ This study reported 65.3% of all the ACL injuries consist of noncontact mechanism. Comparing the mechanisms based on the sexes, 56.9% of male soccer and basketball athletes suffered noncontact ACL injuries, and 68.4% of female athletes who participate in the same sports experienced noncontact ACL injuries. When the data was analyzed by sex and sports, the results were very similar to the above study done by Arendt and Dick.⁸ The male soccer players showed slightly more contact than noncontact ACL injuries (72 contact vs. 66 noncontact ACL injuries). On the other hand, female soccer players demonstrated 1.4 times higher noncontact compared to

contact ACL injuries (115 contact vs. 161 noncontact ACL injuries). In a sport of basketball, male basketball players suffered noncontact ACL injuries 2.1 times higher than contact ACL injuries (37 contact vs. 78 noncontact ACL injuries). However, the rate of female basketball players suffered noncontact ACL injuries is 3.1 times higher than contact mechanism (100 contact vs. 305 noncontact ACL injuries). Compared the noncontact ACL injury rates solely based on sexes, college female soccer and basketball athletes suffered ACL injury incidents 2.7 times higher than their male counterparts (253 total ACL injuries from male soccer and basketball athletes vs. 681 total ACL injuries from female soccer and basketball athletes).

A few other studies reported comparable findings. A prospective study analyzed elite European male and female soccer players documented 62% of all the observed ACL injuries were noncontact in nature.¹⁵⁶ A study examined a type of ACL injury mechanisms in women's college basketball reported that 64% of all ACL injury mechanisms occurred in the games are noncontact.⁴ Another report that conducted retrospective interviews to ACL injured individuals noted that 72% of their injury mechanisms were noncontact.¹³ Using male and female European handball players, a study analyzed number of ACL injuries based on positions.¹¹¹ According to the study, 84% of all ACL injuries come from back and wing position players and 95% of the ACL injuries in the particular position players were noncontact in nature.

Summary

The ACL pathomechanics are classified by three schemes: direct, indirect, and non contact mechanisms. Based on the NCAA epidemiological data and other studies, 60-70% of the ACL injuries accompany with noncontact mechanism. Regarding the sex differences, females are susceptible to the noncontact ACL injury by 10-20% compared to their male counterparts.

Because all reviewed studies expressed the direct and indirect mechanisms as a contact ACL injury, it is difficult to estimate the rate of direct and indirect ACL injuries separately.

Under the noncontact mechanism, ACL is likely to be strained or torn by a resultant force created by human movements, which can be triggered by a loss of trunk control. The loss of trunk control, especially lateral flexion, can cause excessive GRF due to asymmetrical movement patterns, which is compensated by hip musculature, and ACL bundles can be strained or torn. For the indirect mechanism, an external force application to other body parts except for knee joint may trigger the whole cascade of events described above and result in tear of ACL. An external force application to a knee joint directly, which promote knee abduction and anterior tibial translation with internal and external rotations, is likely to cause a direct contact ACL injury.

The available data confirmed that approximately 60-70% of all the ACL injury is noncontact in nature.^{3, 8, 13, 111, 156} The NCAA female soccer and basketball athletes demonstrated 2.7 higher overall ACL injury incidents compared to male athletes who participate in the same sports.³ Additionally, epidemiological data indicated that prevalence of noncontact ACL injury mechanism in female athletes is approximately 10-20% higher than their male counterparts.^{3, 8} From the evidence, it can be interpreted that young female athletes are the most susceptible to noncontact ACL injuries.

Since approximately 60-70% of all ACL injuries are noncontact in nature, it is estimated that rest of the ACL injury mechanisms (30-40%) involves a contact mechanism including either direct or indirect contact. All referenced studies did not differentiate between direct and indirect contact mechanisms and actually combined them as a contact mechanism.^{3, 4, 8, 13, 111, 156} Thus, it

is difficult to estimate a distribution of the direct and indirect mechanisms within the contact mechanism of ACL injuries.

The Problem

Although ACL reconstruction (ACLR) surgery is commonly performed for individuals with ACL tear, the ACLR is not an ultimate solution for ACL care. A study showed 23% of high school age athletes actually re-tear their either contralateral or reconstructed ACL within one year from return to their sports after ACLR.¹²¹ Additionally, 42% of female soccer players who had ACLR demonstrated radiographic osteoarthritis (OA) signs within 10 years from the surgery, and 75% of them commented the OA symptoms negatively affect their quality of life.⁷⁹ Therefore, a potential solution is to find modifiable risk factors to reduce future risk of ACL injury. Several prospective studies found biomechanical and neuromuscular risk factors for future ACL injury,^{55,167} and neuromuscular training (NMT) is often utilized as an intervention to alter the modifiable biomechanical and neuromuscular risk factors. However, although many types of NMT programs were developed and implemented, there is no consensus for effectiveness of the NMT interventions to reduce ACL injury in physically active female population.

Purpose

There were five primary purposes of this dissertation, and each purpose was the following:

1. To identify common pathomechanics of ACL injury and also describe how ACL is injured during each of these pathomechanics.
2. To provide an up to date analyses aimed to determine the effectiveness of neuromuscular training interventions designed to reduce both noncontact and overall

ACL injury risk in female athletes through relative risk reduction and numbers-needed-to-treat analyses.

3. To investigate whether or not compliance of neuromuscular training plays a role in reducing ACL injury incidents in young female athletes.
4. To investigate effect of compliance of proximal neuromuscular training, a trunk and hip focused integrative neuromuscular training, on isokinetic hip abductor strength in young female athletes.
5. To determine the effect of a core integrative neuromuscular training compliance on hip abductor, hamstrings and quadriceps peak torque and hamstrings:quadriceps ratio in young female athletes.

Overview

This dissertation consists of the methods, results, discussion, limitations and conclusions for each of the five purposes. Chapter 2 examined effectiveness of neuromuscular training based on previously published clinical trials that aimed to reduce ACL injury in physically active young female athletes through relative risk reduction and numbers-needed-to-treat analysis. Chapter 3 investigated effects of neuromuscular training intervention compliance on ACL injury reduction in physically active young female athletes from previously published clinical trials that documented compliance information. Chapter 4 compared isokinetic concentric hip abductor and adductor peak torque and abductor:adductor peak torque ratios between male and female collegiate athletes. Chapter 5 analyzed the effect of trunk and hip focused integrative neuromuscular training compliance based on isokinetic concentric hip abductor, hamstrings, quadriceps peak torque and hamstrings:quadriceps ratio in female high school athletes. Finally, Chapter 6 summarizes the results from each chapter and integrates these findings with clinical implications.

Operational Definitions

For the purpose of a clear and concise communication, the following definitions will be used:

1. Neuromuscular training: Physical activity that aims to enhance neuromuscular functions.
2. Compliance: Attendance, participation and completion of assigned neuromuscular training sessions.
3. Anterior cruciate ligament (ACL): A combination of several ligamentous fibers runs from posterior part of the medial side of the lateral condyle to anterior intercondylar area between a transverse meniscal ligament and medial side of medial meniscus.
4. Hip abductors: Gluteus medius, gluteus minimus, tensor fasciae latae, and sartorius
5. Hamstrings: Biceps femoris, semitendinosus, and semimembranosus
6. Quadriceps: Rectus femoris, vastus medialis, vastus lateralis, and vastus intermedius

Assumptions

The primary assumptions for this dissertation were the following:

For chapter 2:

1. A number of subjects and ACL injury incidents in both experimental and control groups were accurately recorded in reviewed clinical trials.

For chapter 3:

1. A number of subjects and ACL injury incidents in both experimental and control groups were accurately documented in reviewed clinical trials.
2. A number of completed intervention sessions were accurately recorded in reviewed clinical trials.

3. Percentages of subjects who attended intervention sessions were accurately noted in reviewed clinical trials.

For chapter 4:

1. Subjects recalled their medical history accurately and provided correct information.
2. Subjects clearly understood instructions of isokinetic test.
3. Subjects performed isokinetic tests with the best of their abilities.

For chapter 5:

1. Subjects clearly understood verbal and written questions and provided correct information in pre- and post-intervention tests.
2. Subjects clearly understood instructions of isokinetic tests in pre- and post-intervention tests.
3. Subjects performed isokinetic tests with the best of their abilities in pre- and post-intervention tests.
4. Intervention providers instructed all exercises as they learned in training session or described in booklet or DVD.
5. Subjects clearly understood instructions of intervention providers.
6. Subjects performed assigned exercises with the best of their abilities.
7. Intervention providers accurately recorded all intervention sessions.
8. Intervention providers accurately transferred the recorded information to a study coordinator.

Delimitations

The primary delimitations of each chapter were the following:

For chapter 2:

1. Clinical trials published before January 1, 1995 were not included.
2. Clinical trials written in non-English languages were not included.
3. Clinical trials published with abstract or poster formats were not included.
4. Clinical trials written as a dissertation were not included.

For chapter 3:

1. Clinical trials published before January 1, 1995 were not included.
2. Clinical trials written in non-English languages were not included.
3. Clinical trials published with abstract or poster formats were not included.
4. Clinical trials written as a dissertation were not included.
5. Clinical trials did not have adequate information for completed intervention sessions were not included.
6. Clinical trials did not present percentage of subjects who attended intervention sessions were not included.

For chapter 4:

1. Only males and females between ages of 18-24 were employed as subjects.
2. Only NCAA Division II women's volleyball, women's basketball, men's basketball, baseball and tennis players were employed as subjects.
3. Subjects were tested in a different phase of their seasons. (Pre- or In-season)

For chapter 5:

1. Only middle and high school girls' basketball, soccer and volleyball players in the Boone county public school system were employed as subjects.
2. Mechanism of checking accuracy of intervention session documentation was lacking.

Limitations

The primary limitations of each chapter were the following:

For chapter 2:

1. Clinical trials that demonstrated negative results were less likely to be published so that they were not included in this study.

For chapter 3:

1. Nearly half of the reviewed clinical trials did not document sufficient information for compliance so that they were not included in this study.
2. Half of the reviewed clinical trials measured subjects' participations to intervention based on individual level whereas the other half reviewed clinical trials used team as a unit of measures.

For chapter 4:

1. No kinematic data including knee abduction moments or angles were taken.
2. No objective measurement for intensity of prescribed exercises.
3. Hip abductor peak torque measures were concentric instead of eccentric contraction. The eccentric contraction is more closely related to function of various athletic movements.

For chapter 5:

1. Randomization between intervention and control groups was not ideal.
2. Cross-contamination between intervention and control groups occurred.
3. Several teams did not have adequate time to perform assigned intervention during pre-season.
4. It was unclear how rigorously the compliance information was tracked by intervention providers.

Figure 1.1. ACL of left knee. (Held by the small silver scissor)

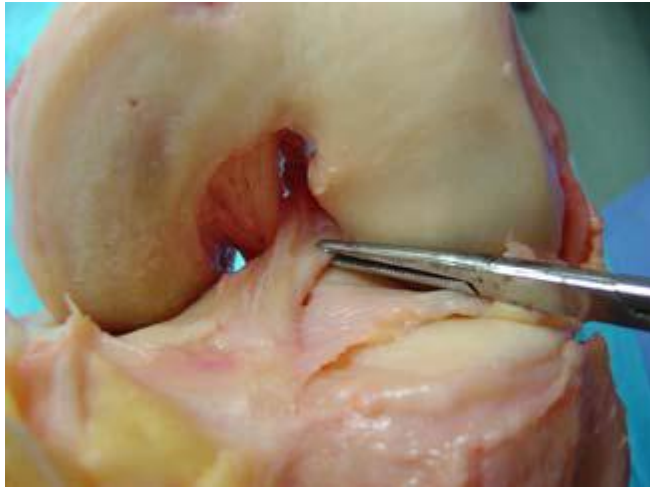


Figure 1.2. Distal attachment of the ACL. The dotted circle is foot region.

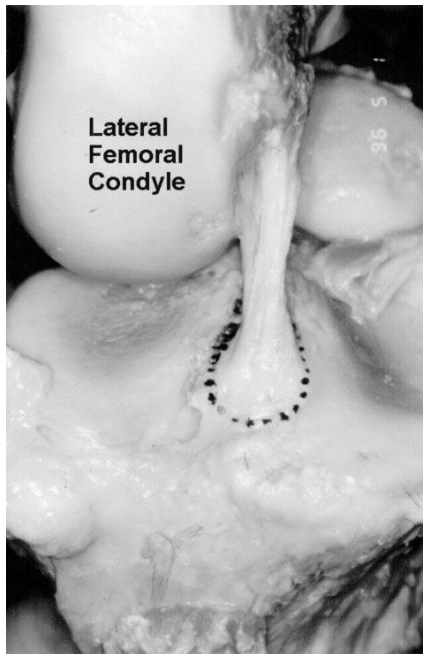


Figure 1.3. Length and width of ACL.

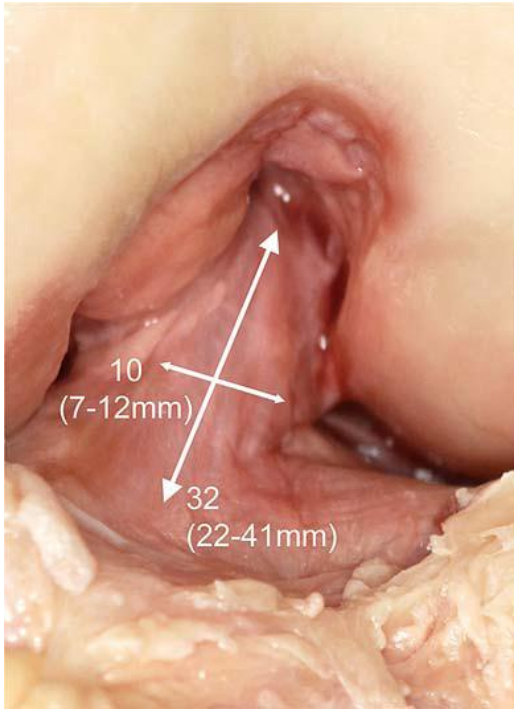
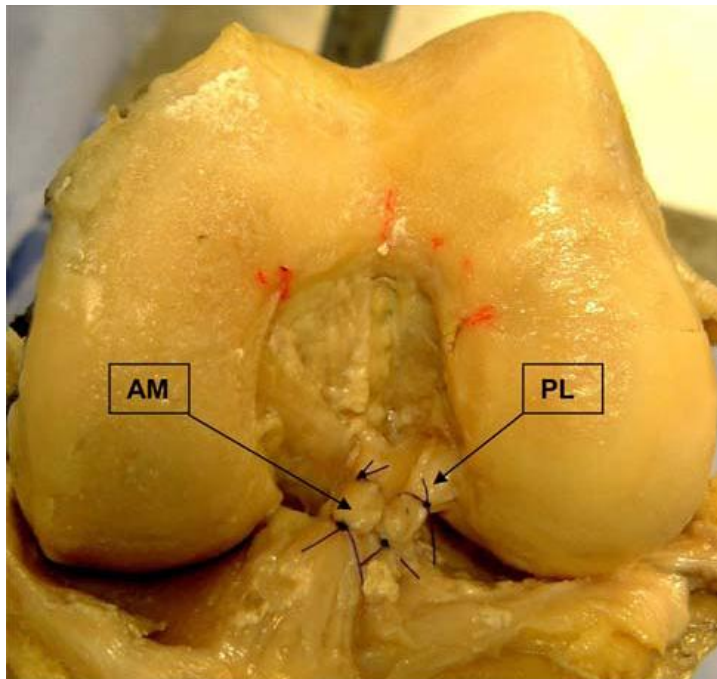


Figure 1.4. Bundles of ACL. AM: Anteromedial bundle. PM: Posteriolateral bundle. Intermediate bundle is not shown in the below picture.



Chapter 2 Evaluation of the Effectiveness of Neuromuscular Training to Reduce Anterior Cruciate Ligament (ACL) Injury in Female Athletes: A Critical Review of Relative Risk Reduction (RRR) and Numbers-Needed-to-Treat (NNT) Analyses

Introduction

Each year, it is estimated that 250,000 ACL reconstruction surgeries are performed in the United States.¹⁶¹ The average cost associated with ACL injuries, including diagnostic tests, surgery and rehabilitation, is conservatively estimated to be \$17,000 per each reconstructive case from 1999 data.⁴⁵ In sum, the financial burdens associated with ACL reconstruction surgery is estimated to be more than \$2 billion annually.¹³⁹ Time lost from ACL injury can be six months^{19,27} or longer. In addition to these substantial financial and time costs associated with ACL injury, various negative consequences have been documented such as mood disturbance⁹³ as well as increased risks of a second ACL injury.¹²¹ Specifically, female athletes who suffer ACL injuries are more likely to experience premature osteoarthritis⁸ and a reduced quality of life due to limited knee function.^{79, 80}

Approximately 70% of ACL injuries occur with a noncontact mechanism^{4, 13, 14} and the rate of ACL injury occurrence in female athletes is higher in cutting, jumping, and pivoting sports compared to males.^{9, 47, 131} Risk factors^{47, 52, 54, 131} associated with neuromuscular control are potentially modifiable and may reduce the risk of noncontact ACL injury.⁵⁶ Since the 1990s, several prospective cohort studies have been performed to determine the effect of neuromuscular training interventions targeted to reduce ACL, knee, and other lower extremity injuries.^{16, 43, 50, 53, 70, 83, 110, 115, 122, 125, 140, 141, 146} Studies often utilized single or limited training modes in their neuromuscular training interventions such as plyometric exercises, balance exercises, or a combination of both.^{16, 53, 110, 140} More comprehensive approaches have been initiated recently,

which consist of a combination of different types of exercises such as plyometrics, strengthening, stretching, and balancing training. The “Dynamic Neuromuscular Analysis (DNA) training,”⁵⁶ “Prevent Injury and Enhance Performance (PEP),”^{43, 83} “11,”¹⁴⁶ and “11+”¹⁴² programs are examples of comprehensive neuromuscular training protocols. In addition, some components of the newly developed neuromuscular training protocols include sports specific exercises.⁷⁰ However, prophylactic effectiveness of those neuromuscular training programs has shown mixed results.

To assess the effectiveness of various neuromuscular training programs, Grindstaff et al. applied relative risk reduction (RRR) and number-needed-to-treat (NNT) analyses on the available neuromuscular training cohort studies that aimed to reduce ACL injury in female athletes.⁴⁸ The analyses demonstrated a 70% total RRR in subjects in the intervention groups compared to those in control groups. Furthermore, the NNT analysis concluded that 89 was the minimum number of athletes needed to prevent one noncontact ACL injury per competitive season.⁴⁸ However, since this previous assessment of the effectiveness of neuromuscular training⁴⁸ the number of large scale cohort studies has nearly doubled, which warranting reassessment of the effectiveness of ACL injury reduction achieved through neuromuscular training interventions. Therefore, the purpose of the current analysis was to provide an up to date analyses aimed to determine the effectiveness of neuromuscular training interventions designed to reduce both noncontact and overall ACL injury risk in female athletes through RRR and NNT.

Methods

Literature Search

A literature search was performed using the PubMed and EBSCO (CINAHL, Medline, SPORT Discus) database from 1995 to 2011 in January, 2012. The key words searched were

performed by applying a combination of following words: “knee”, “anterior cruciate ligament”, “ACL”, “prospective”, “neuromuscular”, “training”, “female”, and “prevention” (Table 2.1). Studies were limited to English language, human subject investigations. The following inclusionary criteria were applied: 1) the number of ACL injury incidents were reported, 2) a neuromuscular training intervention that aimed to reduce ACL incidence was applied, 3) a control group was used, 4) a prospective controlled trial study design was employed, and 5) females were included as subjects. Abstracts, posters, and unpublished data were excluded. Literature found by the key word search was screened in a step by step procedure based on the above inclusionary criteria. During this process, a potential inclusion of studies that hold very similar characteristics of the above five inclusionary criteria were considered. Egger’s regression was used to examine a potential risk of publication bias.

Quality of Methodology Evaluation Method

The Physiotherapy Evidence Database (PEDro) scale is a widely used measurement tool and was employed to analyze methodological quality of the included studies.^{16, 43, 50, 53, 70, 83, 110, 115, 122, 125, 140, 141, 146} Two reviewers independently examined the methodological quality of each study using the PEDro scale. Discrepancies between reviewers were settled by arbitration and consensus.

Level of Evidence and Strength of Recommendation Assessment Method

To evaluate the quality of the current analysis, the Centre of Evidence Based Medicine (CEBM)–Levels of Evidence was implemented. The CEBM-Level of Evidence is used to assess the research design quality of the included studies and facilitates the generation of a grade of strength (A, B, C, and D) of recommendation for the current analyses.

Data Extraction

The number of ACL occurrences in each group (control and intervention), the number of athletes in each group (control and intervention) and athletic exposures were extracted from each study. Whether or not the ACL injuries were contact or noncontact in nature was also extracted from each study. When the mechanism of injury was not documented as either contract or noncontact, an email was sent to the corresponding author in the original paper asking for the mechanism of the ACL injuries. From studies that had both male and female subjects^{53, 83} only data regarding female subjects were utilized. To calculate athletic exposure data, the number of hours and days of participation were extracted from each study. Each day of participation was estimated as two hours and then converted to hours of participation as, used in previous studies.⁴⁸

Operational Calculations

The number of ACL injuries, number of athletes and athletic exposures in both the intervention and control groups were extracted from each study and used to calculate the NNT and RRR. Initially, the control event rate (CER) and intervention event rate (IER) were calculated:

$CER = \# \text{ ACL-injured subjects in control group} / \text{total number of subjects in the control group}$

$IER = \# \text{ ACL-injured subjects in intervention group} / \text{total number of subjects in the intervention group}$

Absolute risk reduction (ARR), the absolute difference in event rate between control and intervention groups, was then calculated:

$ARR = CER - IER$

The inverse of the ARR is used to calculate NNT and was based on the number of athletes across one competitive season. It is mathematically expressed:

$$\text{NNT} = 1 / \text{ARR}$$

A positive NNT value represents a beneficial preventive effect due to the intervention and is referred to as numbers needed to treat to benefit (NNTB). Conversely, a negative NNT value is indicative of a harmful effect and is referred to as numbers needed to treat to harm (NNTH). If the ARR is zero, the NNT values would approach infinity (∞), indicating no beneficial or harmful effects and meaning that an infinite number of athletes might have been needed to demonstrate the benefit or harm from the given intervention.

Relative risk reduction (RRR) was then calculated using the following formula:

$$\text{RRR} = [1 - (\text{IER} / \text{CER})] \times 100$$

The RRR value indicates the percentage by which the intervention reduces risk compared to the controls. Positive RRR values suggest reduced risk by the given intervention. In contrast, negative RRR values indicate increased risk compared to the controls. In addition, 95% of confidence intervals (CI) were calculated for all NNT and RRR values.¹² A set of matrix laboratory (MATLAB) codes was made and used for the NNT and RRR calculation with 95% CI.

Results

A total of 440 unique publications were collected including cross-referenced studies, and 11 studies met the inclusionary criteria. One study that did not completely fulfill the inclusion criteria because of an absence of control group due to the study design was actually included since the study met the purpose of current project. Thus, a total of 12 studies were included in the current analyses (Figure 2.1). The neuromuscular training of each study is summarized in Table

2.2 and the relevant methodological quality as evaluated by the PEDro scores is expressed in Table 2.3. The noncontact and overall ACL injury incidence rates in each group, NNT, RRR, and 95% CI were reported in Tables 2.4 and 2.5. The mean PEDro score was 4.3/10 for the 12 reviewed studies. Two studies^{115, 146} were rated as high as 7 /10 while two studies^{122, 125} were classified 2/10 in PEDro score.

Summaries of Included Studies

Hewett et al. in 1999⁵³ (PEDro score 3, level of evidence 2b)

This research team used a prospective cluster study design and provided six weeks of neuromuscular training, consisting of weight training, plyometrics, and flexibility, to a total of 43 teams (volleyball, soccer and basketball) from area high schools. Each neuromuscular training session lasted 60 to 90 minutes and took place three times per week for six weeks. Certified athletic trainers and physical therapists gave technique instructions and the training sessions progressed through three phases: I) Technique phase, II) Fundamental phase, and III) Performance phase. The 15 girls' teams that received the intervention (6 weeks of neuromuscular training) consisted of 366 athletes: 185 volleyball (50.5%), 97 soccer (26.5%), and 84 basketball (23.0%) players. An ACL incidence rate of the intervention group was 0.06 per 1000 hours of Athletic-Exposure (1000h AE) in the intervention group and 0.11 per 1000h AE in the control group.

Soderman et al. in 2000¹⁴⁰ (PEDro score 4, level of evidence 2b)

This prospective randomized controlled trial provided 10 to 15 minutes of balance training utilizing dynadiscs and balance boards to a total of 221 soccer players for six months. After randomization, 121 athletes (seven teams) were assigned to the intervention group and 100 athletes (six teams) were assigned to the control group. The athletes in the intervention group

were asked to perform the balance training with balance boards every day for the first month.

After the first month, training was decreased to three days per week. This study reported an ACL incidence rate of 0.68 per 1000h AE in the intervention group and 0.12 per 1000h AE in the control group.

Heidt et al. in 2000⁵⁰ (PEDro score 5, level of evidence 1b)

This research group employed a 75 minutes long custom-made speed and agility program to 42 randomly selected high school age soccer players for a total of 21 sessions (1st session is an orientation) over seven weeks. The randomly selected subjects in the intervention group commuted to a local fitness gym to perform the intervention program in pre-season. Over the course of four months, an ACL injury rate in the intervention group was 2.38%, and 3.10% in the control group. This study did not record or report exposure data.

Myklebust et al. in 2003¹¹⁰ (PEDro score 5, level of evidence 2b)

A three year prospective cross-over study (the first year was an observational year, whereas the two subsequent years were intervention periods) recruited a total of 1705 female handball athletes playing for the top three Norwegian handball leagues. A 15 minute session of balance exercises with mats and wobble boards was implemented three days per week in the initial five-seven weeks, which was subsequently reduced to once a week for the remainder of the handball season (approximately five months). During the study period, an ACL incidence rate were: control (Year 1) 0.14 per 1000h AE, intervention (Year 2) 0.13 per 1000h AE, and intervention (Year 3) 0.09 per 1000h AE were recorded.

Mandelbaum et al. in 2005⁸³ (PEDro score 3, level of evidence 2b)

Using a prospective cluster cohort study design, the research team applied a neuromuscular and proprioceptive program to a total of 1885 female soccer players (1041

subjects in 1st year and 844 in 2nd year) and compared the number of ACL injuries to age- and skill- matched controls. The program was a 20 minutes in duration which consisted of education, basic warm-up, stretching for trunk and lower extremity, strengthening for trunk and lower extremity and plyometrics, and was performed two to three sessions per week. This investigation reported an ACL incidence rate of 0.04 per 1000h AE in the intervention group and 0.24 per 1000h AE in the control group over two competitive soccer seasons.

Olsen et al. in 2005¹¹⁵ (PEDro score 7, level of evidence 1b)

With cluster randomized controlled trial design, a 15 to 20 minute long structured warm-up program was implemented to improve awareness of neuromuscular control, balance and strength of knees and ankles in running, cutting, and landing techniques in Norwegian handball players (808 subjects in the intervention group). The structured warm-up program had four different exercises (warm-up, technique, balance, and strength and power), and each exercise was progressed with increasing the level of difficulty. The structured warm-up program was performed in 15 consecutive sessions and then once a week during one competitive Norwegian handball season. During the study period, an ACL incidence rate in the intervention group was 0.03 per 1000 AE, whereas the control group was of 0.10 per 1000h AE.

Petersen et al. in 2005¹²² (PEDro score 2, level of evidence 2b)

A prospective cohort study incorporated 10 minutes of injury prevention training into a team warm-up. The injury prevention training program consisted of improving awareness of injury mechanisms and prevention strategies, balance-board exercises and jump training and was executed three times per week in the preseason and once a week in competition period. Lower extremity injuries were tracked in 134 female handball players who performed the training program and compared with age- and skill- matched controls. The study reported an ACL

incidence rate 0.04 per 1000 h AE in the intervention group and 0.21 per 1000 AE in the control group.

Pfeiffer et al. in 2006¹²⁵ (PEDro score 2, level of evidence 2b)

This research team implemented a 20 minute plyometric-based exercise program twice a week in high school female soccer, volleyball, and basketball athletes for two years. The plyometric-based exercise program, “Knee Ligament Injury Prevention” (KLIP), was developed by various healthcare practitioners and experts. A total of 577 athletes (43 teams) were classified in intervention group, and 862 athletes (69 teams) were categorized into control group. During the investigation, an ACL incidence rate of 0.08 per 1000h AE in the intervention group and 0.04 per 1000 AE in the control group were documented.

Steffen et al. in 2008¹⁴⁶ (PEDro score 7, level of evidence 1b)

Using a cluster-randomized controlled trial (113 teams, 2100 players), this research team prescribed 15 minutes of a structured warm-up program called “11”. The 11 , which consisted of core stability, balance, plyometrics, and hamstrings strengthening exercises, was applied to 1073 young female soccer players (51 teams) for the first 15 consecutive sessions and once a week for the remaining seven and half months. The study documented an ACL incidence rate of 0.06 per 1000 h AE in the intervention and 0.08 per 1000 h AE in the control group.

Gilchrist et al. in 2008⁴³ (PEDro score 4, level of evidence 1b)

In the randomized cluster controlled study, investigators applied the 20 minute long program, previously reported by Mandelbaum et al.⁸³ to high level college female soccer teams. The intervention and control groups were paired and formed a cluster. The clustered pairs were purposefully allocated different geographic regions throughout the US. Then, one cluster of each region was randomly selected for the study. Soccer players (583 players, 26 teams) classified in

the intervention group performed the program three times per week for the entire fall soccer season (twelve weeks). An ACL incidence rate in the intervention group was 0.20 per 1000h AE, whereas the ACL incidence rate in the control group was 0.34 per 1000 h AE.

Kiani et al. in 2010⁷⁰ (PEDro score 4, level of evidence 2b)

This prospective cluster control trial (97 teams, 1506 players) included a 20-25 neuromuscular regimen consisting of a running warm-up, isometric contraction of lower extremity muscle groups, balance exercises with jump components, strengthening of lower extremities and core stability to 777 young soccer players (48 teams) two days per week for the two month pre-season and once a week during six months of in-season sessions. This study reported an ACL incidence report of 0 per 1000 h AE in the intervention group and 0.08 per 1000 h AE ACL incident rate in the control group.

LaBella et al. in 2011⁷³(PEDro score 6, level of evidence 1b)

Using a randomized cluster controlled design, investigators applied a program called “Knee Injury Prevention Program” (KIPP). A total of 737 athletes: 321 soccer (43.6%), and 416 basketball (56.4%) players practiced the KIPP, which comprised 20 minutes of progressive strengthening, plyometric, balance, and agility exercises three times per week for one competitive season. Over the course of the study, an ACL incidence rate of 0.10 per 1000 h AE was documented in the intervention group and 0.48 per 1000 h AE ACL incidence rate was documented in the control group.

Data Synthesis

For synthesis of the 12 included studies, the RRR for noncontact ACL injury from the reviewed studies was 73.4% (95% CI = 62.5% to 81.1%) in subjects who performed the assigned neuromuscular training programs compared to subjects who were allocated in the control group

(Table 2.4). The RRR for overall ACL injuries was 43.8% (95% CI = 28.9% to 55.5%) for subjects in the intervention group compared to subjects who were in the control group (Table 2.5). The NNT analysis indicated that it was necessary to intervene upon 108 athletes (95% CI = NNTB 86 to 150) in order to prevent 1 noncontact ACL injury (Table 2.4). For overall ACL injuries, the NNT analysis indicated that 120 athletes (95% CI = NNTB 74 to 316) are needed to participate in neuromuscular training programs to show prophylactic effects of preventing one injury (Table 2.5).

Bias Assessment

The bias assessment for the 12 included studies was performed using Egger's regression. The Egger's regression intercept was -0.29 (95% CI: -2.20, 1.61, $P = 0.37$, one tailed), indicating that publication bias was not detected in the current analysis (Figure 2.2).

Evidence Synthesis

The CEBM level of evidence of each study is listed in the Table 1. The CEBM level of evidence can further generate a grade of strength of recommendation based on the level of consistent evidence, which consists of A to D. In the current analysis, five of the included studies were rated as level 1b, while seven studies were rated as level 2b. Based on consistency of the results from included studies, the strength of recommendation grade for the current evidence is B (consistent level of 2 or 3 studies or extrapolations from level 1 studies).

Discussion

The aim of this systematic review of the literature was to identify effectiveness of neuromuscular training programs in preventing noncontact and overall ACL injury incidence in large scale studies published from 1995 to 2011 using RRR and NNT. The RRR for noncontact

ACL injury was 73.4% and 43.8% for overall ACL injuries, with confidence intervals that do not encompass zero. It can be interpreted that female athletes who performed a given neuromuscular training program have 73.4% less risk to suffer a noncontact ACL injury compared to those who did not perform NMT. Similarly, 43.8% of overall ACL injury risk reduction can be obtained in female athletes who performed neuromuscular training compared to those who served in a control group. To our knowledge, this may be the first study to report prophylactic effects of NMT on the overall ACL injury risk.

Recent ACL injury classification recommendations suggest four different types of ACL injury: direct contact, indirect contact, classic noncontact, and other noncontact.⁸⁴ The noncontact ACL injuries resulted from an individual's own movements without contact by another person or object, which typically disturbed by some types of perturbation.⁸⁴ The classic noncontact ACL injury mechanism involves cognitive perturbation, which is defined as a disruption to the planned motor task that requires a rapid update to the intended motor control plan.⁸⁴ Unexpected sudden movement or position give perturbation to one's cognition, and the ACL is torn, which is often observed in athletic setting. Conversely, other noncontact ACL injuries occur in simple activities in daily living, sometimes without any specific mechanism, and seemingly no cognitive perturbation was applied.⁸⁴ The other two types of ACL injury mechanisms, direct and indirect contact, involves physical perturbation either direct to the knee joint or other body parts at the time of or immediately before the injury.⁸⁴ Since both of the classic and other noncontact ACL injury mechanisms do not entail the physical perturbation, it was assumed the prophylactic effects of neuromuscular training are only applicable to noncontact ACL injury. However, the current analysis identified prophylactic effects to overall ACL injuries, which include direct

contact and indirect contact mechanisms, in addition to the classic and other noncontact ACL injuries.

Two previous studies^{52, 164} that analyzed large scale neuromuscular training interventions targeted to reduce ACL incidence, demonstrated lower RRR than the current analysis. A meta-analysis of a total of seven randomized controlled and prospective cohort studies that aimed to reduce ACL injuries among female athletes by neuromuscular training interventions showed 60% of RRR (95% CIs = 40% to 73%) between athletes in the intervention and control groups.¹⁶⁴ This analysis did not separate ACL injuries based on mechanism (either noncontact or contact): thus, it can be inferred that 60% of RRR is a reflection of neuromuscular training for a combination of noncontact and overall ACL injuries. Another RRR study based on five prospective neuromuscular training intervention trials aimed to reduce ACL injuries in female athletes documented 70% of RRR (95% CIs = 54% to 80%).⁵² The study included only noncontact ACL cases for the analysis; therefore, it is interpreted that the neuromuscular training can effectively reduce 70% of noncontact ACL risks in female athletes compared to subjects in the control groups. The current analysis included several recently published studies, and 73.4% (95% CIs = 62.5% to 81.1%) of RRR for noncontact ACL injury were comparable to the previous reports. Based on the RRR numbers, it can be interpreted that it is possible to prevent approximately three-quarters of noncontact ACL injuries by applying a neuromuscular training intervention (Table 2.4). Furthermore, the current analysis found that neuromuscular training can effectively reduce overall ACL injury risks by 43.8% (95% CI = 28.9% to 55.5%) (Table 2.5).

Through examining neuromuscular training programs that demonstrated greater than 73.4% and 43.8% of RRR in noncontact and overall ACL injuries^{16, 43, 50, 53, 70, 83, 110, 115, 122, 125, 140, 141, 146}, a few common characteristics were observed. It appears that those programs combined

multiple types of exercises instead of one neuromuscular training type.^{16, 43, 50, 53, 70, 83, 110, 115, 122, 125, 140, 141, 146} Strengthening, plyometric, and balance exercises were primarily employed in those programs.^{16, 43, 50, 53, 70, 83, 110, 115, 122, 125, 140, 141, 146} Unlike those programs, several studies included in the current analysis that did not show high RRR rates applied a single type of neuromuscular training.^{110, 125, 140} Two studies^{110, 140} implemented a set of balance exercises and one study¹²⁵ tested the effectiveness of plyometric exercises. Synthesizing the information altogether, providing one type of neuromuscular exercise is not adequate to generate prophylactic effect; however, combining multiple types of exercises seems to enhance the effectiveness of neuromuscular training in female athletes.

In contrast, the NNT values obtained from the current analysis were quite different from the previously reported values. The current NNT analysis demonstrated 108 (95% CI = NNT 86 to 150) and 120 (95% CI = NNT 74 to 316) for noncontact and overall ACL incidences. It is interpreted that 108 athletes are needed to prevent one noncontact ACL injury as well as 120 athletes for overall ACL injury. Previous research in NNT to reduce the risk of noncontact ACL injury was reported at NNT=89 (95% CI = NNT 66 to 136), which is notably fewer than the current analysis.⁴⁸ The higher NNT value for overall ACL injury prevention in the current study may be a result of the inclusion of studies that did not demonstrate favorable prophylactic effects to the subjects in intervention groups. For instance, the previous NNT analysis⁴⁸ did not include a prospective randomized control study¹⁴⁰ published in 2000. The study actually observed more ACL incidence in the intervention group instead of the control group (Table 2.2). Additionally, a recently published study with a cluster randomized controlled trial design¹⁴⁶ was not included in the previous report, but was included in the current analysis. The study did not demonstrate strong prophylactic neuromuscular training effects in the intervention group. (Table 2.4 and 2.5)

From a study quality standpoint, the previously published NNT analysis had one randomized controlled trial¹¹⁵ whereas the current analysis comprises five randomized controlled trials.^{43, 50, 73, 115, 146} Another analysis is imperative to find a link between the quality of the study and number of ACL injuries. However, these study results were likely to influence the higher NNT values in the current analysis compared to previous reports.

Coaches and clinicians may be hesitant to implement an intervention program with a NNT of 108 for noncontact ACL injuries and 120 for overall ACL injuries. The time commitment for preventing one ACL injury may appear too substantial. For instance, to generate neuromuscular training prophylactic effects, a female soccer team that consists of 20 players needs to keep performing a neuromuscular training programs for over five competitive seasons (20 players x 5 seasons = NNT 100) to prevent one noncontact ACL injury. Estimating that there are approximately 15 players on one handball team, eight competitive seasons (15 athletes x 8 seasons = NNT 120) are required to reach the NNT 120, which is the estimated number needed to prevent one overall ACL injury. The lengthy time commitment for preventing one ACL injury may not be a primary interest of coaches and healthcare providers. Additionally, most neuromuscular training programs take approximately 15-20 minutes to complete,^{16, 43, 50, 53, 70, 83, 110, 115, 122, 125, 140, 141, 146} which coaches may feel is “too much,” especially during in-season. In fact, most studies performed in Europe reduced the frequency of the neuromuscular training session during in-season compared to pre-season.^{16, 43, 50, 53, 70, 83, 110, 115, 122, 125, 140, 141, 146} Those factors may lead to a difficulty of neuromuscular training program inception and potentially low compliance. In fact, several reviewed studies pointed that low compliance of assigned neuromuscular training programs as a limitation of the studies.^{16, 43, 50, 53, 70, 83, 110, 115, 122, 125, 140, 141, 146}

A potential approach to improve compliance to injury prevention intervention is to explain additional benefits associated with neuromuscular training. One of the reviewed studies demonstrated not only the positive effects on ACL injury, but also significantly lower rates of injury to other knee ligaments, and reduced moderate and major acute knee or ankle injuries rate in those who performed neuromuscular training compared to those who did not.¹¹⁵ Similarly, fewer overall knee injuries were reported in subjects in the intervention group compared to the control group in one reviewed study.⁷⁰ Another reviewed study also showed lower ankle sprain injury rates in the intervention group.⁷³ Performance enhancement is an added benefit to neuromuscular training as demonstrated in one investigation which used pediatric aged girls and boys (mean age = 10 ± 1 years old) revealed improvements in balance and vertical jump height after nine weeks of injury prevention program implementation.²⁴ This study stated that those performance changes may help gaining support from coaches and potentially increase compliance to the preventive neuromuscular training.

The current analysis generated effectiveness of neuromuscular training as an intervention to prevent noncontact and overall ACL injuries. However, a significant number of athletes are needed to demonstrate prophylactic effects of the neuromuscular training; thus, the next logical step is to establish a method to screen athletes for injury risk. To detect potential at-risk athletes for future ACL injury, the current gold standard is usage of a three-dimensional laboratory based motion analysis system. This system is specialized to capture the three (sagittal, frontal, and transverse) plane kinematic motions with high frequency cameras. However, it requires expensive equipment, extensive time, and skillful biomechanists to analyze the data. To make the screening more efficient and applicable to larger populations, development of a valid and reliable tool with low cost and high efficiency is ideal. Several screening methods, aimed to identify at-

risk athletes for future ACL injury without the three-dimensional laboratory motion analysis, were developed and introduced in recent publications.^{86, 104, 118}

In place of the expensive three-dimensional motion analysis cameras, several screening tools were recently introduced using two-dimensional cameras. A landing error scoring system (LESS) was a clinical screening tool generated by Padua and his research team.¹¹⁸ Two standard video cameras are placed to capture the athlete's landing kinematics from sagittal and frontal plane views. The landing patterns captured by the video cameras were examined and provided a total error score. Another tool developed by Myer and colleagues used a nomogram scale, which consists of total points from a combination of static (body mass and tibia length) and dynamic (knee valgus motion, knee flexion range of motion, quadriceps/hamstring strength ratio) measures captured with two standard video cameras.¹⁰⁴ Also, a study conducted by Stensrud et al. utilized a standard video camera to capture an image of knee joint alignment in the frontal view during dynamic movements.¹⁴⁷ However, validation of those two-dimensional video screening tools for a clinical use is warranted in future studies.

Limitations

Several limitations to this study should be stated. Although each study was carefully reviewed, only half^{43, 53, 70, 83, 125} of the reviewed studies (5/12) documented the nature of the ACL injury mechanism. The lead author contacted the corresponding authors of each study. However, only one¹⁴⁶ out of the six studies who did not document the nature of the injury mechanism responded with full information. When the corresponding authors did not respond to the question, the status of ACL injury mechanism was cited from the previously published study.⁴⁸ The lead author contacted a primary author of the study and assured accuracy of the ACL mechanism information presented.⁴⁸

One study¹¹⁰ did not meet one of the inclusion criteria, which was a presence of control group; however, the study was included in the current analysis. The study had a large sample size with a good methodological quality (PEDro score 5/10) so that it was too difficult to exclude. The study implemented a cross-over study design instead of prospective cohort design and the intervention periods were actually two years followed by a one year of control period. Therefore, the current analysis extracted only one year (first year) of intervention and control period.

Wide varieties of neuromuscular training programs were noted across the reviewed studies (Table 2.2). Frequency, duration and intensity varied across studies; therefore, even though the RRR 73.7% and 43.8% for noncontact and contact ACL injuries were found, it was difficult to point out what frequency, duration and intensity would maximize the neuromuscular training prophylactic effect to reduce future ACL injury risk among female athletes. Furthermore, different types of neuromuscular training were applied to different sports, ages and study designs. All of those variables made this analysis challenging to identify imperative aspects of neuromuscular training.

Conclusion

A review of 12 large scale neuromuscular training studies aimed to lower ACL injuries in female athletes demonstrated RRR of 73.4% and 43.8% for noncontact and overall contact ACL injury. Neuromuscular training may reduce not only noncontact ACL injury risk, but also overall ACL injury risk, which includes contact ACL mechanisms (direct and indirect). NNT analysis estimated that 120 athletes need to perform a neuromuscular training program to prevent one overall ACL injury. Similarly, the NNT estimated 108 athletes need to execute a neuromuscular training program to prevent one noncontact ACL injury. Although the current analysis demonstrated prophylactic effectiveness of neuromuscular training, the NNT values yielded high

NNT values, which may cause a difficulty in gaining support from a coaching staff. However, several studies documented benefits of neuromuscular training beyond ACL injury prevention, which include reduction in other knee and ankle injuries and performance improvement. Another possible direction is to reduce the NNT is to identify at-risk athletes using two dimensional camera systems, which have begun showing potential, but more studies are needed for these tools to be implemented in clinical use. Future training prophylactic effects to specific populations (gender, age, and sports) as well as pursue more efficient methods to identify at-risk athletes. The resulting findings could lead to a more desirable outcome for ACL injury prevention and could promote safe and long lasting athletic participation in physically active population.

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Table 2.1. Stepped PubMed/EBSCOhost Search Strategy With the Number of Studies
 Abbreviations: TIAB, title and abstract. Date was limited from January 1, 1995 to December 31, 2011. Language was limited in English. Species were limited in humans. Sex was limited in female. CINAHL, MEDLINE, and SPORT Discus were included in the EBSCO search.

Step	Strategy	PubMed	EBSCO
#17	Search (#11) AND (#16)	390	59
#16	Search (#12) OR (#13) OR (#14) OR (#15)	23899	18522
#15	Search “preventing” [TIAB]	4916	996
#14	Search “preventive” [TIAB]	2373	2143
#13	Search “prevent” [TIAB]	8219	1660
#12	Search “prevention” [TIAB]	12956	1367
#11	Search(#5) AND (#10)	4151	2185
#10	Search (#6) OR (#7) OR (#8) OR (#9)	73052	62290
#9	Search “female” [TIAB]	14981	15682
#8	Search “training” [TIAB]	9806	24398
#7	Search “neuromuscular” [TIAB]	1412	2278
#6	Search “prospective” [TIAB]	50692	20738
#5	Search (#1) OR (#2) OR (#3) OR (#4)	12480	53232
#4	Search “ACL” [TIAB]	411	1001
#3	Search “anterior cruciate ligament” [TIAB]	554	4001
#2	Search “knee” [TIAB]	4827	17026
#1	Search “injury” [TIAB]	7824	
			33140

Table 2.2. Summary of Reviewed Studies including Study Design, PEDro Score, Sports, Number of Teams, Ages, Type, Length, Frequency and Duration

Reference (Year)	Study design	Level of evidence	Sports	Number of teams	Ages	Type	Length	Frequency	Duration
Hewett et al. (1999)	Prospective non-randomized cohort	2b	Soccer Volleyball Basketball	15 teams (control) 15 teams (intervention)	14 – 18 yr (range)	Stretching, plyometrics, Weight training	60 – 90 minutes	3 days per week in pre-season	6 weeks
Soderman et al. (2000)	Prospective randomized control	2b	Soccer	6 teams (control) 7 teams (intervention)	C:20.4 ±5.4 yr I: 20.4 ±4.6 yr (mean)	Balance with dynadiscs and balance boards	10 – 15 minutes	Each day for 30 days. 3 days per week rest of the season	6 months
Heidt et al. (2000)	Prospective randomized control	1b	Soccer	258 individuals (control) 42 individuals (intervention)	14 – 18 yr (range)	Cardiovascular, Plyometrics, Strength, flexibility, agility, and sports specific drills	75 minutes	3 days per week in pre-season	7 weeks
Myklebust et al. (2003)	Prospective non-randomized cross over	2b	Handball	60 teams (1 st yr) 58 teams (2 nd yr) 52 teams (3 rd yr)	21-22 yr (mean)	Balance with mats and wobble boards	15 minutes	3 days per week for 5-7 weeks. Once a week for rest of the season	One competitive handball season (5 months)
Mandelbaum et al. (2005)	Prospective non-randomized cohort	2b	Soccer	207 teams (control) 97 teams (intervention)	14-18 yr (range)	Basic warm-up, stretching, strengthening, plyometrics, and agility	20 minutes	2-3 times per week in in-season	3 competitive soccer seasons (12 weeks per season)
Olsen et al. (2005)	Prospective cluster randomized controlled	1b	Handball	59 teams(control) 61 teams (intervention)	16-17 yr (mean)	Warm-up, technique, balance, strength and power	15-20 minutes	15 consecutive sessions. Once a week for rest of the season	One competitive handball season (5 months)
Petersen et al. (2005)	Prospective matched cohort	2b	Handball	10 teams(control) 10 teams (intervention)	C:19.8 I: 19.4 yr (mean)	Education, balance-board exercise, jump training	10 minutes	3 times per week in pre-season. Once per week for rest of the season	8 weeks
Pfeiffer et al. (2006)	Prospective non-randomized cohort	2b	Soccer Volleyball Basketball	69 teams(control) 43 teams (intervention)	14-18 yr (range)	Plyometrics	20 minutes	2 times per week in in-season	One competitive season (4-5 months)
Steffen et al. (2008)	Prospective block randomized controlled	1b	Soccer	51 teams (control) 58 teams (intervention)	15.4 yr (mean)	Core stability, balance, plyometrics	15 minutes	15 consecutive sessions. Once a week for rest of the season	7.5 months
Gilchrist et al. (2008)	Prospective cluster randomized controlled	1b	Soccer	35 teams (control) 26 teams (intervention)	C:19.9 I: 19.9 yr (mean)	Basic warm-up, stretching, strengthening, plyometrics, and agility	20 minutes	3 times per week in in-season	One competitive soccer season (4-5 months)
Kiani et al.	Prospective		Soccer	49 teams	C: 15.0	Core	20-25	2 days per	9 months

(2010)	cluster non-randomized cohort	2b		(control) 48 teams (intervention)	I: 14.7 yr (mean)	strengthening, balance	minutes	week for 2 months. Once a week for rest of the season	
LaBella et al. (2011)	Prospective cluster randomized controlled	1b	Soccer Basketball	53 teams (control) 53 teams (intervention)	C: 16.2 yr (mean) I: 16.2 yr (mean)	Strengthening, plyometrics, balance, agility	20 minutes	3 times per week in pre- and in-season	One competitive season (8-17 weeks)

* Although the study was a randomized controlled design, the follow-up rate was low (51.2%). Therefore, the level of evidence was rated as 2b.

Table 2.3. Physiotherapy Evidence Database Scores of the Reviewed Studies

Reviewed Studies	Total Scores	PEDro scale										
		1	2	3	4	5	6	7	8	9	10	11
Hewett et al. (21)*	3	-							X	X	X	
Soderman et al. (22)	4	-	X		X						X	X
Heidt et al. (20)	5	-	X					X	X	X	X	
Myklebust et al. (23)*	5	-						X	X	X	X	X
Mandelbaum et al (24)*	3	-							X		X	X
Olsen et al. (25)	7	-	X		X			X	X	X	X	X
Petersen et al. (26)*	2	-									X	X
Pfeiffer et al. (27)*	2	-									X	X
Steffen et al. (28)	7	-	X	X				X	X	X	X	X
Gilchrist et al. (29)	4	-	X		X						X	X
Kiani et al. (30)*	4	-			X			X			X	X
LaBella et al. (41)	6	-	X	X					X	X	X	X

X “yes” score. Blank “no” score. PEDro scale is optimized for evaluation of randomized control trails, thus the PEDro assessment score for the non-randomized control should be interrupted with caution. Studies with * are not randomized trial. 1. Eligibility criteria specified, 2. Random allocation of subjects, 3. Allocation concealed, 4. Similar groups at baseline, 5. Blinding of subjects, 6. Blinding of intervention providers, 7. Blinding of outcome assessors, 8. Outcomes obtained from 85% of subjects, 9. Use of intent-to-treat analysis if protocol violated, 10. Between group statistical comparison, 11. Point measures and measures of variability.

Table 2.4. Relative Risk Reduction (RRR) and Numbers-Needed-to-Treat Analyses for Noncontact ACL injury.

Reference	Noncontact ACL injury in group	Female athletes per group	Noncontact ACL incidence rates*	RRR (95% confidence interval)	NNT to benefit (NNTB) [†] NNT to harm (NNTH) [‡] (95% confidence interval)
Hewett et al. Control	5 0	463 366	0.11 0	100 (NA)	93 NNTB (50 NNTB to 723)
Intervention					
Myklebust et al. Control	18	942	0.09	38.8	135 NNTB
Intervention (1 st year only)	10	855	0.03	(-0.9, 62.9)	(53 NNTB to ∞ to 255 NNTH)
Mandelbaum et al. Control	67 6	3818 1885	0.24 0.04	81.9 (60.9, 91.6)	70 NNTB (52 NNTB to 106)
Intervention (1 st and 2 nd yr total)					
Olsen et al. Control	5 1	778 808	0.06 0.01	80.7 (-64.5, 97.7)	193 NNTB (89 NNTB to ∞ to 1079 NNTH)
Intervention					
Petersen et al. Control	5 0	142 134	0.21 0	100 (NA)	28 NNTB (16 NNTB to 205)
Intervention					
Pfeiffer et al. Control	3 3	862 577	0.04 0.08	-49.4 (-637.6, 69.7)	582 NNTH (188 NNTB to ∞ to 114 NNTH)
Intervention					
Gilchrist et al. Control	10 2	583 852	0.18 0.06	86.3 (37.8, 97.0)	68 NNTB (39 NNTB to 265)
Intervention					
Steffen et al. Control	2 3	947 1073	0.03 0.05	-32.4 (-690.6, 77.8)	1462 NNTH (277 NNTB to ∞ to 201 NNTH)
Intervention					
Kiani et al. Control	5 0	729 777	0.08 0	100 (NA)	146 NNTB (78 NNTB to 1153)
Intervention					
LaBella et al.					

Control	6	755	0.48	65.9	191 NNTB
Intervention	2	737	0.10	(-13.5, 89.7)	(80 NNTB to ∞ to 470 NNTH)
Total					
Control	126	10019	0.14	73.4	108 NNTB
Intervention	27	8064	0.04	(62.5, 81.1)	(86 NNTB to 150)

*Relative Incidence Rate (per 1000 A*h) † NNT to benefit (NNTB) represents a beneficial preventive effect of the intervention. ‡ NNT to harm (NNTH) indicates harmful effect of the intervention. Infinity (∞) means no beneficial or harmful effects.

Table 2.5. Relative Risk Reduction (RRR) and Numbers-Needed-to-Treat (NNT) Analyses for Overall ACL injury.

Reference	Overall ACL injury in group	Female athletes per group	Overall ACL incidence rates*	RRR (95% confidence interval)	NNT to benefit (NNTB) [†] NNT to harm (NNTH) [‡] (95% confidence interval)
Hewett et al. Control	5	463	0.11	49.4	187 NNTB
Intervention	2	366	0.06	(-159.3, 90.1)	(58 NNTB to ∞ to 149 NNTH)
Soderman et al. Control	1	78	0.12	-403.2	19 NNTH
Intervention	4	62	0.68	(-4289.0, 42.3)	(70 NNTB to ∞ to 9 NNTH)
Heidt et al. Control	8	258	NA ⁺	23.2	139 NNTB
Intervention	1	42		(-498.3, 90.1)	(17 NNTB to ∞ to 22 NNTH)
Myklebust et al. Control	29	942	0.14	12.6	257 NNTB
Intervention (1 st only)	23	855	0.06	(-19.0, 35.9)	(52 NNTB to ∞ to 86 NNTH)
Olsen et al. Control	9	778	0.10	67.9	127 NNTB
Intervention	3	808	0.03	(-18.1, 91.3)	(61 NNTB to ∞ to 1334 NNTH)
Petersen et al. Control	5	142	0.21	78.8	36 NNTB
Intervention	1	134	0.04	(-18.1, 91.3)	(17 NNTB to ∞ to 170 NNTH)
Gilchrist et al. Control	18	583	0.34	73.4	44 NNTB
Intervention	7	852	0.20	(36.7, 88.8)	(27 NNTB to 136)
Steffen et al. Control	5	947	0.08	29.4	644 NNTB
Intervention	4	1073	0.06	(-162.2, 81.0)	(135 NNTB to ∞ to 231 NNTH)
Total Control	80	4191	0.14	43.8	120 NNTB
Intervention	45	4192	0.06	(28.9, 55.5)	(74 NNTB to 316)

*Relative Incidence Rate (per 1000 A*h) [†]Exposure information was not available in the original report. [‡] NNT to benefit (NNTB) represents a beneficial preventive effect of the intervention. [‡] NNT to harm (NNTH) indicates harmful effect of the intervention. Infinity (∞) means no beneficial or harmful effects.

Figure 2.1. Flow chart of literature search

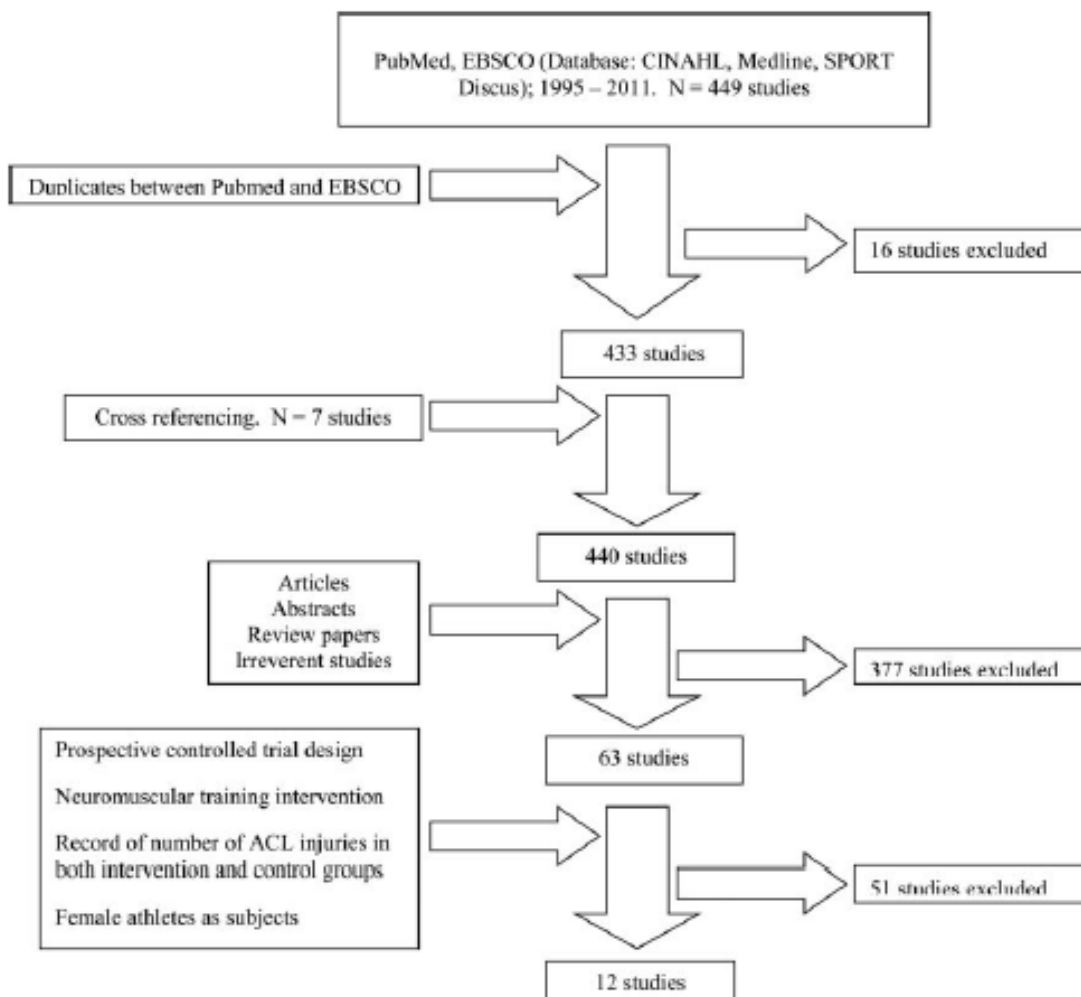
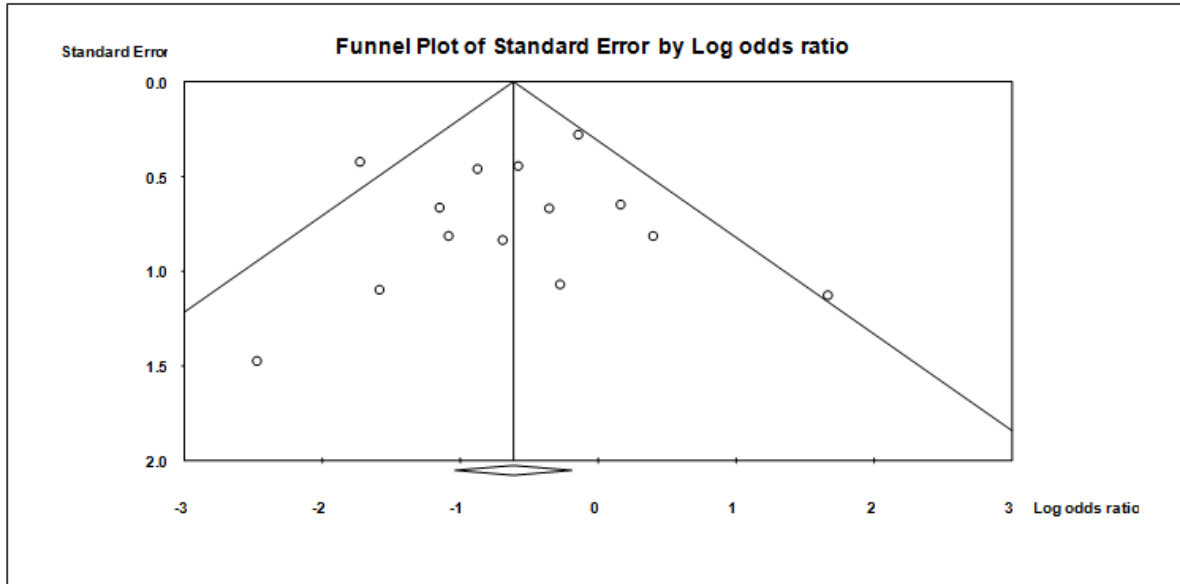


Figure 2.2. Forest plot for publication bias



Each circle represents a reviewed study. Asymmetry of the circle distribution and circle(s) outside of the diagonal line indicate presence of publication bias. No publication bias was detected from the above forest plot.

Chapter 3 Effect of Compliance with Neuromuscular Training on ACL Injury Risk Reduction in Female Athletes: A Meta-Analysis

Introduction

The incidence rate of ACL injuries among the general population is calculated to be one in 3000, and it is estimated that about 100,000 individuals suffer ACL injuries in the United States annually.⁶⁵ Approximately 250,000 ACL reconstruction surgeries are performed annually in the US¹⁶¹ with a conservative estimate average cost of \$11,500-17,000 per case.^{45, 53} In sum, the financial burdens caused by ACL injuries are likely near \$3 billion annually.⁸⁵ In addition to the financial costs, individuals who suffer from ACL injuries experience premature osteoarthritis^{80, 114} and reduced quality of life due to the limited knee function.⁷⁹

It is accepted that noncontact ACL injury rates among females are higher when compared to their male counterparts.^{9, 78} Several factors have been identified to explain this gender disparity^{40, 87, 95}; however, a single factor to predict these gender differences in injury rates has not been identified. Anatomical and hormonal factors such as ACL circumference, joint laxity, and menstrual phase have been discussed as increased risk factors for noncontact ACL injuries in females.^{17, 22, 60} However, it is difficult, if not impossible, to modify these particular risk factors. In contrast, evidence indicates that neuromuscular risk factors are modifiable.⁵⁶

Recently, neuromuscular risk factors such as knee valgus position,^{37, 39, 55} quadriceps/hamstrings muscular activation^{100, 153} and trunk controls^{59, 167} in dynamic motions have been proposed as risk factors for noncontact ACL injuries. In order to modify those risk factors, neuromuscular training intervention trials have been performed.^{16, 43, 53, 70, 83, 110, 122, 140, 141, 146, 158} Since the 1990s, large scale prospective cohort studies have been performed to determine the effect of neuromuscular interventions targeted to reduce ACL, knee, and other lower

extremity injuries. In the 1990s and early 2000s, studies often utilized isolated training modalities in their neuromuscular training interventions such as plyometric exercises, balance exercises, or a combination of both.^{16, 110, 122, 140, 158} Recent neuromuscular interventions are aimed at decreasing not only ACL injuries, but also other lower extremity injuries. This approach is more comprehensive and typically consists of a combination of different types of exercises such as plyometrics, strengthening, stretching, and balancing training. Examples of more recent comprehensive neuromuscular training programs include the “Dynamic Neuromuscular Analysis (DNA) training,”⁵⁶ “Prevent Injury and Enhance Performance (PEP) program,”^{43, 83} “11”¹⁴⁶ and “11+”¹⁴¹ programs. In addition, certain components of these newly developed neuromuscular training include sports specific exercises.^{70, 122, 146} While the exercise selected for use in these programs is comprehensive, the program execution is widely varied.

The reported mode, length, frequency, and duration of neuromuscular interventions have varied considerably in previous investigations, making it challenging to determine specific dose-response effects of neuromuscular training. A systematic review of five large-scale randomized neuromuscular cohort studies aimed to lower noncontact ACL injury found 70% total risk reduction in subjects in intervention group compared to control group.⁴³ The systematic review concluded that neuromuscular interventions are effective in reducing noncontact ACL injury risk.

Although the reduction of the noncontact ACL risk by neuromuscular interventions was reported, the prior work did not examine intervention compliance which is likely an important dimension of neuromuscular training efficacy. Compliance provides an indication of how many athletes completed the assigned intervention, revealing actual effects of neuromuscular training. No prior meta-analysis studies have examined an association between compliance rates and ACL

injury incidence as well as potential barriers to prescribed neuromuscular training. Therefore, the purpose of this meta-analysis was to investigate whether or not compliance of neuromuscular training plays a role in reducing ACL injury incidents in young female athletes. It was hypothesized that neuromuscular training studies with high compliance rates would result in lower ACL incidence rates in young female athletes.

Methods

Literature Search

A literature search of the PubMed, SPORT Discus, CINAHL, and Medline (1995-2010) databases was performed in February 2010. Key words were “anterior cruciate ligament prevention”, “ACL prevention”, “knee prevention”, and “prospective knee prevention”. Language was limited to English. A total of 195 studies were identified. An additional 10 studies were added as a result of cross referencing. The following inclusionary criteria were applied: 1) number of ACL injury incidents were reported, 2) a neuromuscular intervention was applied, 3) females were included as subjects, 4) prospective controlled trial study design was employed, and 5) attendance and compliance information was collected. Abstracts and unpublished data were excluded.

Quality of Methodology Evaluation Methods

Methodological quality of the included studies was analyzed using the Physiotherapy Evidence Database (PEDro) scale. The PEDro scale is a widely utilized measurement tool to rate the methodological quality of the randomized clinical trial with moderate intraclass correlation coefficient values.^{82, 94} Two reviewers independently examined the methodological quality of the each study with using the PEDro. Discrepancies between the reviewers were settled by arbitration and consensus.

Level of Evidence Assessment Methods

To evaluate the quality of the current analysis, the Centre of Evidence Based Medicine (CEBM)–Levels of Evidence chart was implemented.¹¹⁶ The CEBM-Level of Evidence assesses the quality of the included studies with using a combination of numerical and letter scales, which further facilitates generating a grade of recommendation of the current meta-analysis.

Data Extraction

Data regarding the number of ACL injury events, the number of athletes who attended intervention sessions, and the number of completed intervention sessions throughout the season were extracted from included studies. The ACL injury rate was measured from both the control and intervention groups in each study. If the ACL injury type was documented as either contact or noncontact, the number of each injury mechanism was documented, but the total number of ACL injuries was used to calculate the ACL incidence rate. In cases where the necessary attendance and completion data were not reported in the published manuscript, an email was sent to the corresponding author listed in the original paper and asked compliance related questions.

Data analysis

Operational definitions used for the data analysis were listed at Table 3.1. An incidence rate ratio (IRR) was used to make an initial comparison of ACL injury incidence rates in intervention versus control groups. This technique was employed because of its capability of comparing the ratio (control vs. intervention) of incidence rates in multiple groups. The IRR accounts for ACL injury rate upon the different number of athletes and observation time frames of each study. For the observation time periods, months were used as a unit. Specifically, ACL injury percentages and incidence rates of intervention groups of each study were analyzed.

To compare the effect of high compliance versus low compliance, a mean overall compliance rate of the selected studies was initially calculated. Based on the mean overall compliance rate (45.3%), studies with compliance rates above the mean overall compliance rate were categorized as “high” (>45.3%) and those with compliance rates below the mean were categorized as “low” (<45.3%). The IRR with 95% confidence intervals (CI) was used to compare the ACL incidence rates between high and low compliance rate intervention groups. Subsequently, compliance rate was further broken down into “high” (>66%), “moderate” (33-66%), or “low” (<33%) compliance groups. To compare the incidence rates between these tertile categorizations, IRRs with 95% confidence intervals were again calculated.

Results

A total of six out of 205 studies met the inclusion criteria of this meta-analysis. Although an email was sent to the corresponding authors to obtain the necessary attendance and completion data, only two^{140, 146} out of the seven corresponding authors provided sufficient compliance related information (Figure 3.1). Included study characteristics were summarized in Table 3.2. The mean PEDro scale was 4.7 for the six reviewed studies (Table 3.3). One study¹⁴¹ was rated as high as 7 while one study⁵³ as classified as 3 in PEDro scale. Table 3.4 summarizes the ACL injury rate, attendance, completion, and overall compliance rates. The attendance rates were reported as either individual or team basis.

Reviewed Studies

Hewett et al. in 1999⁵³ (PEDro score 3, level of evidence 2b)

This research team used a prospective cluster study design and provided six weeks of neuromuscular training, which consisted of weight training, plyometrics, and flexibility, to a total of 43 teams from 12 local area high school girls’ volleyball, soccer, and basketball teams. Each neuromuscular training session lasted 60 to 90 minutes per session and took place three times per

week for six weeks. The 15 girls teams that received the intervention (6 weeks of neuromuscular training) contained 366 in total athletes: 185 volleyball (50.5%), 97 soccer (26.5%), and 84 basketball (23.0%) players, and ACL incident rate of the intervention group was 0 per 1000 hours of Athletic-Exposure (1000h AE) in volleyball, 0 per 1000h AE in soccer, and 0.12 per 1000h AE in basketball compared to 0 per 1000h AE in volleyball, 0.09 per 1000h AE in soccer, and 0.13 per 1000h AE in basketball per in control group. In this study, 70% of the athletes (248 of 366) in the intervention group completed a minimum of four weeks (66.7%) of the neuromuscular training program sessions. Therefore, the overall compliance rate ($0.70 \times 0.667 = 0.462$) was 46.2% in this study,

Soderman et al. in 2000¹⁴⁰ (PEDro score 4, level of evidence 2b)

This prospective randomized controlled trial provided 10 to 15 minutes of balance training with dynadiscs and balance boards to a total of 221 soccer players for six months. The balance training was performed every day for the first month and decreased to three days per week after the first month. This study reported ACL incidence rate of 0.68 per 1000h AE in intervention group and 0.12 per 1000h AE in control group. In the study, the number of subjects in the intervention group declined from initial 121 to 89 players due to non-athletic or research related reasons. Ultimately, 69.7% (62/89) of subjects completed the intervention session with 44.9% (35 minimum sessions / 78 maximum sessions). The attendance rates and completion rates produced an overall compliance rate ($0.697 \times 0.449 = 0.313$) of 31.3%.

Heidt et al. in 2000⁵⁰ (PEDro score 5, level of evidence 1b)

This research group employed a 75 minutes long custom-made speed and agility program to 42 randomly selected subjects for a total of 20 sessions over seven weeks. Over the course of four months, ACL injury rate in the intervention group was 2.38%, and 3.10% in the control

group (The study did not record exposure data). The study reported 100% attendance and session completion rates. According to a staff member of the research group, the female soccer players who were in the intervention group had attendance monitored by their coaches, leading to a 100% overall compliance rate ($1.0 \times 1.0 = 1$), which could be potentially inaccurate.

Myklebust et al. in 2003¹¹⁰ (PEDro score 5, level of evidence 2b)

A three year prospective cross-over study (the first year was an observational year whereas the two subsequent years were intervention periods) recruited a total of 1705 female handball players. A 15 minute session of balance exercises with mats and wobble boards was implemented three days per week in the initial five – seven weeks, and was subsequently reduced to once a week for the remainder of the handball season (approximately five months). During the study period, ACL incidence rate: control (1998-1999) 0.14 per 1000h AE, intervention (1999-2000) 0.13 per 1000h AE, and intervention (2000-2001) 0.09 per 1000h AE were recorded. According to the study, 26% of the teams in the intervention group fulfilled the criteria: participation in a minimum of 15 neuromuscular training sessions. Based on the frequency and duration of the intervention, the maximum number of neuromuscular sessions was calculated as 30 to 34 sessions, which generated the session completion rate of 44.1 to 50%. Therefore, the first year overall compliance rate ($0.26 \times 0.441 \sim 0.50 = 0.115 \sim 0.13$) ranged from 11.5 to 13%. In the second year, the attendance rate increased to 29%. Therefore, the second year overall compliance rate was calculated in the same manner as the first year, which generated an overall compliance rate ($0.29 \times 0.441 \sim 0.50 = 0.128 \sim 0.145$) of 12.8-14.5%.

Steffen et al. in 2008¹⁴⁶ (PEDro score 7, level of evidence 1b)

Using a cluster-randomized controlled trial (113 teams, 2100 players), this research team prescribed a 15 minute of a structured warm-up program, which consisted of core stability,

balance, plyometrics, and hamstrings strengthening exercises to 1073 young female soccer players (51 teams) for first 15 consecutive sessions and once a week for the remaining seven and half months. The study documented ACL incidence rate 0.06 per 1000 h AE in intervention and 0.08 per 1000 h AE in control group. The original article reported that “14 out of 58 of teams in the intervention completed more than 20 prevention training sessions”. This yields an attendance rate of 24.1%. The 45 total maximum sessions were calculated based on frequency and duration of the assigned intervention method, which was 15 consecutive sessions and then reduced to once a week for the last seven and half months. Based on the maximum number of sessions, the completion rate was calculated to be 44.4% (20/45). The combination of the attendance and completion rates yielded a 10.7% overall compliance rate ($0.241 \times 0.444 = 0.107$).

Kiani et al. in 2010⁷⁰ (PEDro score 4, level of evidence 2b)

This prospective cluster cohort controlled trial (97 teams, 1506 players) included a 40 minute neuromuscular regimen consisting of a running warm-up, isometric contraction of lower extremity muscle groups, balance exercises with jump components, strengthening of lower extremities, and core stability to 777 young soccer players (48 teams) two days per week for the two month pre-season and once a week during six month of in-season. This study reported 0 per 1000 h AE ACL incident rate in intervention and 0.08 per 1000 h AE ACL incident rate in control group. The compliance scale was set into four categories: less than 50%, at least 50%, at least 75%, or 100%. During the preseason, coaches of three teams rated compliance at less than 50%, 36 teams reported compliance of at least 75%, and nine teams reported compliance at 100%. At the end of the season, only three teams reported compliance less than 75%. The 93.8% (45/48) attendance rate and the 75% completion rate generated a 70.3% overall compliance rate ($0.938 \times 0.75 = 0.703$).

Data Synthesis

In summary, the overall compliance rates from the reviewed studies ranged from 10.7% to 100%. The mean overall compliance rate of the six studies was 45.3%. The reviewed studies were initially categorized into either high or low compliance based on the mean overall compliance rate. Three studies^{50, 53, 70} revealed higher overall compliance rates and the other half^{110, 140, 146} showed lower overall compliance rates compared to the mean overall compliance rates. The results of the IRR meta-analysis indicated a statistically lower ACL incidence rates in the high compliance rate studies compared to the low compliance rate studies (IRR 0.27: 95% CI: 0.07, 0.80) (Figure 3.2).

The six reviewed studies were further classified to one of the following categories based on the generated compliance rates: high (compliance rates > 66.6%), moderate (compliance rates between 66.6% - 33.3%), and low (compliance rates < 33.3%) compliance rate studies. Based on this categorization scheme, two studies showed high (> 66.6%) compliance rates^{50, 70} and one study had moderate (66.6% - 33.3%) compliance rates.⁵³ Three studies demonstrated low (< 33.3%) compliance rates.^{110, 140, 146} IRR meta-analysis was applied to the six studies based on the three compliance rate categories (High, moderate, and low). The IRR meta-analysis demonstrated a statistically lower ACL incidence rates in the high compliance rate studies compared to the moderate and low compliance rate studies (IRR 0.18: 95% CI: 0.02, 0.77) (Figure 3.3).

Evidence Synthesis

The CEBM level of evidence for each study was listed on the table 2. In the current analysis, two of the included studies were rated as evidence level 1b, while four studies were rated as evidence level 2b. Based on consistency of the results from the included studies, the

strength of recommendation grade for the current evidence is B (consistent level 2 or 3 studies or extrapolations from level 1 studies).

Discussion

The aim of this meta-analysis was to determine if compliance is associated with ACL injury incidence in individuals participating in a neuromuscular training program. We hypothesized that neuromuscular training with high compliance rates would significantly lower ACL incidence rates in young female athletes and that this reduction would be greatest in the high compliance training groups. The results of this study support our hypothesis demonstrating there may be an inverse relationship between compliance and ACL injury: Higher compliance rates signify a greater reduction in the ACL incidence rates. The findings in this study may be the first to indicate a potential dose-response relationship between neuromuscular training compliance and ACL incidence rates in large scale prospective cohort studies. A wide variety of overall compliance rates were observed, which ranged between 10.7% and 100%. Four of the six studies demonstrated overall compliance rates less than 50%.^{53, 110, 140, 146} In addition, two out of the six studies reported less than 15% compliance, which is quite low.^{110, 146}

In the tertile analysis, the two high-compliance rate studies^{50, 70} generated the ACL incidence rate ratio of 0.18 (95% CI: 0.02, 0.77), which was statistically significant compared to moderate and low compliance studies. The ACL incidence rate ratios of the moderate and low compliance studies were 0.56 (95% CI: 0.05, 3.41), and 0.88(95% CI: 0.53, 1.47), respectively. These findings indicate that subjects in the moderate compliance study (IRR 0.56 [0.05, 3.41]) have a 3.1 greater risk (IRR 0.18 [0.02, 0.77]) of suffering from ACL injuries compared to subjects in the high compliance studies (IRR 0.18 [0.02, 0.77]). Furthermore, the low compliance studies (IRR 0.88 [0.53, 1.47]) showed a 4.9 times greater relative ACL injury risks compared to subjects in the high compliance studies. This information implies how vital it is to maintain high

compliance when using neuromuscular training interventions to reduce ACL injury incidence. More specifically, this study suggests that the overall compliance rate (attendance x completion) needs to be more than 66% to successfully reduce ACL injury risks.

Overall prophylactic effects of neuromuscular training interventions from all six of the reviewed studies resulted in an ACL incidence rate ratio of 0.74 (95% CI: 0.47, 1.15), which did not reveal statistical significance. However, it can be explained that half of the reviewed studies demonstrated low compliance, which weighted the low compliance studies proportionally heavy relative to the proportions of the high and moderate compliance rate studies. Potentially, if more high and moderate studies were found and included in this analysis, the weight of studies would have been more evenly distributed throughout high, moderate, and low compliance study categories, which may have skewed the rate ratio results.

Two studies^{50, 70} demonstrated more than 66% of overall compliance rate. One study,⁷⁰ not only incorporated their interventions with their regular practice warm-up, but made it similar to the existing warm-up method, which might have helped coaches' acceptance and understanding to the program. Although the intervention length was 40 minutes long, the study showed high overall compliance rates (70.4%). This study did not observe any ACL injury in intervention group over the eight month study. Conversely, a total of five ACL injuries were confirmed in the control group, and they were all noncontact mechanisms. This suggests that their neuromuscular training type, length, frequency, and duration were valid and effective in their focused population (intervention group mean age: 14.7) and sport (soccer). Another study⁵⁰ that showed high overall compliance rates did not integrate the intervention with the warm-up. Instead, subjects commuted to a gym club to perform a custom made speed and agility training program as a pre-season workout. Selected subjects were highly encouraged to participate in all

the training sessions by their coaches, which was likely to help leading to the highest overall compliance rate (100%).

On the other hand, half of the studies^{110, 140, 146} did not attain at least 33% of the overall compliance rates. The study¹⁴⁶ that yielded the lowest overall compliance rate (10.7%) in the six studies highlighted low compliance as a limitation of the study and stated that completing only 15 sessions within a 3 month time frame is not effective to show prophylactic effects for ACL injuries. The authors of the study commented that a lack of available scheduling for the intervention program due to a short pre-season, constant competitions, infrequent practice days, and occasional academic and holiday breaks may have contributed to the low compliance. Another low compliance study¹⁴⁰ (31.3%) actually demonstrated higher ACL injury rates (6.45%) in intervention group compared to control group (1.28%). The research team gave a balance board to all subjects in the intervention group, and the training instruction was thoroughly explained. However, the research team asked the subjects to perform the balance board exercise at home instead of making it as a part of practice or team functions. The lack of supervision might have led to low motivation to adhere the balance board exercises, which might have led to low compliance. In fact, the research team commented that maintaining high motivation for the prescribed intervention was a challenge. In addition, the study¹⁴⁰ introduced only single-component neuromuscular training (balance board exercise) to the subjects in the intervention group, which was also seen in another low compliance study.¹¹⁰ The study gave a balance exercise using mats and wobble boards to the subjects.¹¹⁰ A lack of variations in exercises might have resulted in boredom with the intervention, especially in young athletes. Reduced interest might possibly lower the athlete's motivation to participate in the intervention, which may be a reason for the low compliance rates.^{110, 140} A constrain of the restricted time

schedules, a lack of supervision, and limited neuromuscular training exercise variations may account for a major contributing factor the low overall compliance rate.

Furthermore, the disparity between the high and low overall compliance rates may stem from additional benefits and supports in high compliance studies. The study⁵⁰ which demonstrated the highest overall compliance rates used a custom made speed and agility training program as an intervention, which costs \$360.00 for a total of 21 sessions. However, the cost was waived for all subjects in the intervention group in this study. Another study⁷⁰ with the second highest overall compliance rates supplied monthly letters to maintain motivation and adherence to the neuromuscular training. Those incentive based efforts might have played a key role in maintaining the subjects' and coaches' motivations to participate in neuromuscular training, which might have been reflected to the high compliance. Conversely, one low compliance study stated "reduced motivation among coaches and players" as a limitation and can be a potential contributing factor for the low interest in participating in neuromuscular training.¹⁴⁶ This raises the question of how preventive neuromuscular training can be implemented with high compliance without any incentive or additional supports in real athletic practices. The current analysis suggests that the overall compliance rates need to be over 66% in order to demonstrate the prophylactic effects of neuromuscular training. Thus, it is vital to consider strategies to maintain athletes' and coaches' motivation and allocate time to perform a given neuromuscular training on a consistent basis.

Large variances were observed among the neuromuscular training intervention, length, frequency, duration, and methods (Table 3.2). The intervention session length ranged from 10 to 90 minutes per session, and all three studies^{110, 140, 146} that were categorized in low compliance had relatively short (10-15 minutes) session length compared to other studies. The duration of

the intervention varied from six weeks to eight months. However, the two studies^{50, 53} that took more than 60 minutes per intervention session had relatively shorter duration (6 weeks and 7 weeks), and the interventions were just used for their pre-season because once in-season start, time for neuromuscular training is limited. This trend is explained that once in-season schedule starts, time availability for neuromuscular training intervention is limited. With regard to intervention frequencies, a trend was observed in the studies performed in European countries. These studies tended to prescribe the intervention more frequently in earlier parts of the season and intervention frequency tended to decline as the seasons progressed to the more competitive components (end of season tournaments and championships) of the season. Those studies also incorporated interventions as a part of practices, usually with the warm-up.

Along with compliance issues, supervision of the neuromuscular training to ensure proper biomechanical technique should be considered. All studies used intervention providers—generally athletic trainers, physical therapists or coaches—to teach the neuromuscular training to subjects in the intervention groups (Table 3.2). One study⁷⁰ had a physician to educate coaches and athletes in the instructional training (Table 3.2). Five of the six studies provided instructional videos, written materials, and seminars to give specific biomechanical instructions to the intervention providers. Several studies included seminars to train the intervention providers providing theoretical background and practical implementation tips as well as information on proper biomechanical techniques of the neuromuscular exercises.^{110, 146} To ensure intervention providers' execution and abilities, several studies made research team staff members inspect the instructors at the intervention site. One study asked the subjects to perform a neuromuscular training at home instead of team warm-up. Without supervision with an emphasis on proper technique, limited or poor physiologic adaptation to the neuromuscular training exercises might

result in no decrease in injury risk or possibly an increased rate of injury compared to controls (Table 3.2).

Based on this comprehensive review of the literature, there is moderate to strong evidence to support the importance of compliance. Specifically, consistent attendance by involved athletes and commitment to the completion of sessions throughout the intervention period contribute to the effectiveness of the injury prevention program. It is recommended that clinicians make every effort to improve adherence to ACL injury prevention programs in order to receive the desired prophylactic effects.

Limitations

Five studies^{43, 83, 115, 122, 125} that did not document sufficient information for attendance and intervention completion were not included in the analysis. The research team contacted the corresponding authors of each study to obtain necessary information for the overall compliance calculation, but the compliance related information provided from two studies^{43, 83} was not adequate for the current analysis. Three studies^{115, 122, 125} never responded to writer's contacts. Inclusion of these studies could have influenced the result of the current analysis.

Three studies^{50, 53, 140} measured the attendance rates on an individual basis, whereas the other three studies^{70, 110, 146} used the team as a unit to record their attendance (Table 3.4). The different measurement scales may not generate accurate attendance rates, which may influence the overall compliance rate accuracy. Measurement on an individual basis provides more reliable data than on a team basis because it is difficult to determine how many subjects of each team in the intervention groups actually participated in the given intervention if the attendance was calculated by team function.

As well as different measurement scales for the attendance rates, compliance rates scales varied among reviewed studies since each study used own protocol. One study³ used a protocol of more than 66.7% of neuromuscular training session completion as the subjects' inclusion criteria for the data analysis. Another study¹⁴⁰ used 45% as the cutoff point for the minimum neuromuscular training completion. Differences between the compliance cut-score for subject inclusion between investigations influenced the percentage of subjects to be included in the individual study data analysis. However, to maintain the balance between the completed sessions and included subjects, the overall compliance was calculated by a product of both attendance and completion rates.

Only two^{53, 70} out of the six studies documented the nature of the ACL injury mechanism. In general, neuromuscular training is designed to prevent noncontact ACL injuries. If the reported ACL injuries mechanisms were contact in nature, comparing the prophylactic effects of each intervention based on the compliance rate may not be valid. The research team contacted the corresponding authors of each study. However, only one¹⁴⁶ out of the four studies^{50, 110, 140, 146} that did not document the nature of the injury mechanism responded with full information; thus the IRRs were calculated based on all ACL injuries, not just noncontact ACL injuries.

The current meta-analysis focused on compliance. Therefore, it does not reflect the primary effects of neuromuscular training. Contents of the neuromuscular training were diverse and demonstrated wide variety between high and low compliance studies. Because different types of neuromuscular training were prescribed in different sports, ages, and study designs, it is difficult to identify which type of exercises are the most likely to prevent ACL injuries.

Conclusion

Among the six neuromuscular intervention studies with sufficient compliance information, our meta-analysis demonstrated that higher compliance was associated with lower ACL incidence rates among physically active young females. Compared to subjects in the high compliance study (IRR 0.18 [0.02, 0.77]), subjects in the moderate compliance study (IRR 0.56 [0.05, 3.41]) show a 3.1 times greater risk of suffering from ACL injuries. Moreover, subjects in low compliance studies (IRR 0.88 [0.53, 1.47]) demonstrated a 4.9 times greater relative ACL injury risks compared to subjects in the high compliance studies (IRR 0.18 [0.02, 0.77]). This indicates a potential inverse dose-response relationship between neuromuscular training compliance and ACL incidence in young female athletes. The study findings implied that attending and completing the prescribed neuromuscular training sessions is an integral component of ACL prevention. Incorporation of the neuromuscular training intervention in a warm-up, or as a part of regular practices, is a practical strategy to enhance compliance and ensure proper technique. Also, finding a strategy to maintain athletes' adherence to neuromuscular training may be necessary to enhance compliance. Those strategies could lead to a more consistent outcome of ACL injury reduction and could promote safe and long lasting athletic participation in physically active young females.

Acknowledgements

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Table 3.1. Operational Definitions for Data Analysis

Operational Terms	Definitions
ACL injury (%)	Number of ACL injury event(s) / Total number of subjects in the intervention or control groups
ACL injury incidence rates (athletes-months)	Number of ACL injury event(s) / The total number of athletes in a group x Observation time periods (months)
Attendance rates (%)	The number of subjects who completed the minimum amount of session criteria in the study / Total number of subjects in the intervention group
Completion rates (%)	The number of sessions completed in the study / Maximum sessions offered to the intervention group.
Overall compliance rates (%)	Attendance rate x Completion rate
Incidence rate ratio (IRR)	A meta-analysis method to compare the odds ratio of incidence rates between control and intervention groups in multiple studies.

Table 3.2. Summary of Reviewed Studies

Study Year	Study Design (CEBM - Level of Evidence)	Sports	Size (Number of Athletes)	Age	Intervention providers
Hewett et al. 1999	Prospective cluster cohort (2b)	Volleyball Soccer Basketball	C=15 teams (463) I=15 teams (366)	14 – 18 yo	Athletic trainers Physical therapists
Soderman et al. 2000	Prospective randomized cluster cohort (2b)*	Soccer	C=6 teams (78) I=7 teams (62)	C:20.4±5.4 yo I:20.4±4.6 yo	Physical therapists
Heidt et al 2000	Prospective randomized (1b)	Soccer	C=258 players I=42 players	14 – 18 yo	Athletic trainers
Myklebust et al. 2003	Prospective cross-over (2b)	Handball	C=60 teams (942) 1 st I=58 teams (855) 2 nd I=52 teams (850)	Overall mean age is 21 – 22 yo	Physical therapists
Steffen et al. 2008	Prospective randomized cluster cohort (1b)	Soccer	C=51 teams (947) I=58 teams (1073)	Overall mean age is 15.4±0.8 yo	Norwegian Football Association certified coaches Physical therapists
Kiani et al 2010	Prospective cluster cohort (2b)	Soccer	C=49 teams (729) I=48 teams (777)	C: 15.0 yo (13.0, 17.6) I:14.7 yo (12.7, 18.6)	Physician Physical therapist Coaches

* Although the study was a randomized controlled design, the follow-up rate was low (51.2%). Therefore, the level of evidence was rated as 2b.

C = Control group I = Intervention group

Table 3.2. Summary of Reviewed Studies Continued

Study Year	Intervention Type	Intervention			ACL injury (mechanism)
		Length	Frequency	Duration	
Hewett et al. 1999	Stretching, plyometrics, weight training	60 – 90 min	3 days per week	6 weeks	C: 5 (5 noncontact) I: 2 (2 noncontact) * 1 ACL+MCL)
Soderman et al. 2000	Balance with dynadiscs and balance boards	10 – 15 min	Each day for 30 days. Then, 3 days per	6 months	C: 1 (no report) I: 4 (no report) *1 ACL+MCL)

			week for rest of the season		
Heidt et al 2000	Sports specific cardiovascular , plyometrics, cord drills, strengthening, stretching	75 min	20 sessions. (2 treadmill and 1 plyometric based session per week)	7 weeks	C: 8 (no report) I: 1 (contact)
Myklebust et al. 2003	Balance with mats and wobble boards	15 min	3 days per week for 5- 7 weeks. Then, once a week for rest of the season.	5 months	1 st year ('98 – '99) C: 29 (no report) 2 nd year ('99 – '00) I: 23 (no report) 3 rd year ('00 – '01) I: 17 (no report)
Steffen et al. 2008	Core stability, balance, plyometrics	15 min	15 consecutive sessions. Then, once a week for rest of the season.	7.5 months	C: 5 (2 noncontact) I: 4 (3 noncontact)
Kiani et al 2010	Core strengthening, balance	40 min	2 days per week for about 2 months. Once a week for rest of the season.	9 months	C: 5 (5 noncontact **2 ACL+MM) I: 0

No report means there is no description of the ACL injury mechanism

*A combination of ACL and Medical Collateral Ligament (MCL) injuries

**A combination of ACL and Medical Meniscus injuries

Table 3.3. Physiotherapy Evidence Database Scores of the Reviewed Studies

PEDro Scale	Hewett et al (3)*	Soderman et al (20)	Hedit et al (33)	Myklebust et al (21)*	Steffen et al (27)	Kiani et al(28)*
1.Eligibility criteria specified	-	-	-	-	-	-
2.Random allocation of subjects		X	X		X	
3.Allocation concealed					X	
4.Similar groups at baseline		X				X
5.Blinding of subjects						
6.Blinding of intervention providers						
7.Blinding of outcome assessors			X	X	X	X
8.Outcomes obtained from 85% of subjects	X		X	X	X	
9.Use of intent-to-treat analysis if protocol violated	X		X	X	X	
10.Between group statistical comparison	X	X	X	X	X	X
11.Point measures and measures of variability		X		X	X	X
Total Scores	3	4	5	5	7	4

X “yes” score. Blank “no” score. PEDro scale is optimized for evaluation of randomized control trials, thus the PEDro assessment score for the non-randomized control should be interrupted with caution. Studies with * are not randomized trial.

Table 3.4. Summary of ACL injury, Attendance, Completion, and Overall Compliance Rates.

Study Year	ACL injury rates	Attendance rates	Completion rates	Overall Compliance rates
Hewett et al. 1999	C = 1.08% I = 0.55%	70% per individual	66.6%	46.2%
Soderman et al. 2000	C = 1.28% I = 6.45%	69.7% per individual	44.9%	31.3%
Heidt et al 2000	C = 3.10% I = 2.38%	100% per individual	100%	100%
Myklebust et al. 2003	C = 3.08% 1 st I = 2.69% 2 nd I = 2.00%	1 st I = 26% per team	47.1% (1 st year average)	12.3% (1 st year average)
		2 nd I = 29% per team	47.1% (2 nd year average)	13.7% (2 nd year average)
Steffen et al. 2008	C = 0.59% I = 0.69%	24.1% per team	45.4%	10.7%
Kiani et al. 2010	C = 0.69% I = 0.00%	93.8% per team	75%	70.4%

C = Control group

I = Intervention group

ACL injury rates = Number of ACL injury event(s) / Subject(s) in the group (either control or intervention)

Attendance and Completion rates were extracted or calculated from original literature.

Overall compliance rate = Attendance rate x Completion rate

Figure 3.1. Flow chart of literature search

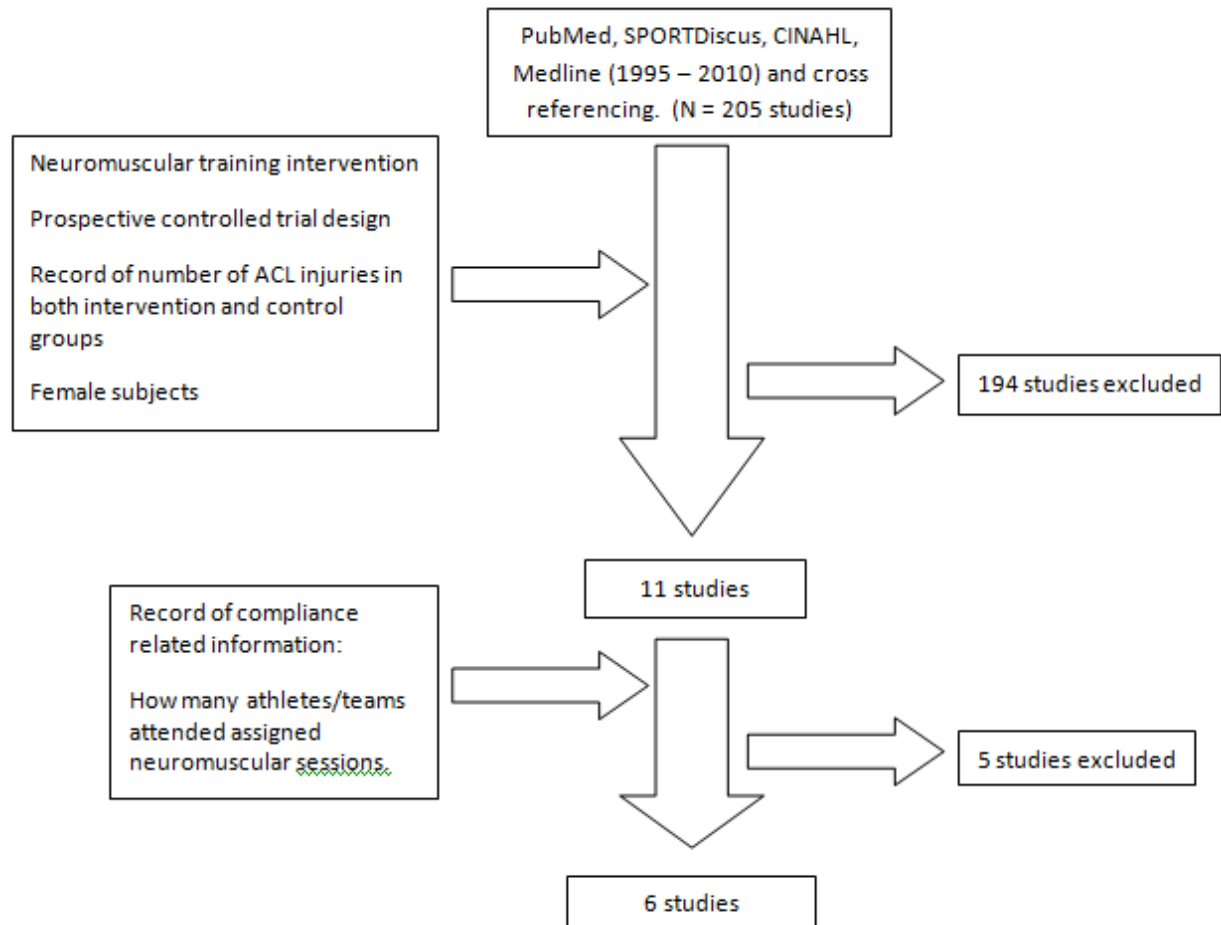
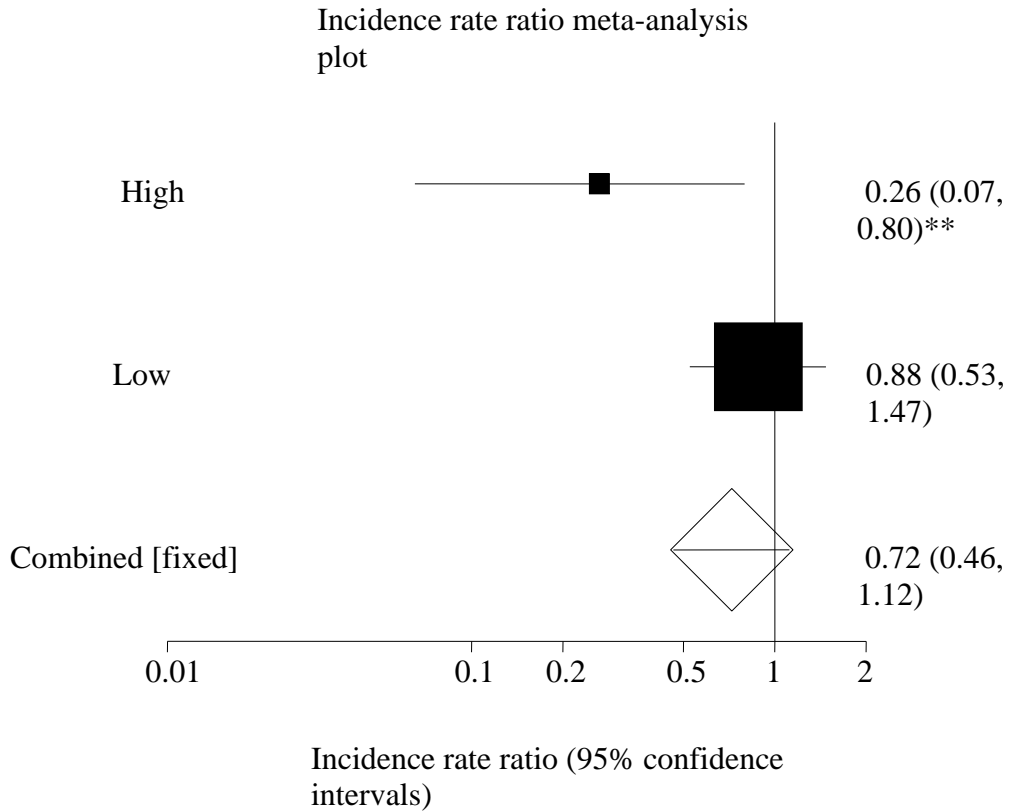
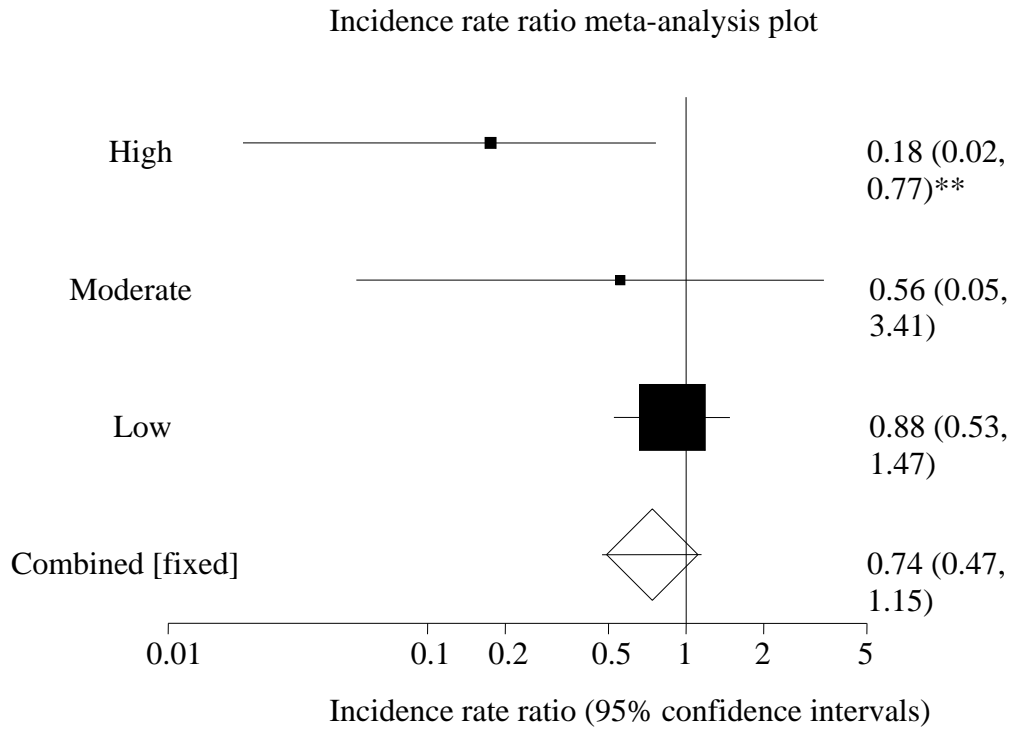


Figure 3.2. Incidence rate ratio between high and low compliance studies



** High compliance studies demonstrated statistically lower incident rate ratio (IRR 0.26: 95% Confident Intervals: [0.07-0.80]) compared to low compliance studies.

Figure 3.3. Incidence rate ratio in high, moderate and low compliance studies



** High compliance studies demonstrated statistically lower incident rate ratio (IRR 0.18: 95% Confident Intervals: [0.02-0.77]) compared to moderate and low compliance studies.

Chapter 4 Effect of Compliance on Trunk and Hip Integrative Neuromuscular Training on Hip Abductor Strength Development in Female Athletes

Introduction

Recent studies demonstrate a mechanistic link between reduced proximal neuromuscular control and increased risk for knee and ACL injuries in the female athletic population. Reduced hip abductor strength has been noted in individuals with patellofemoral pain syndrome (PFPS) compared to non-PFPS individuals.^{15, 18, 66} In addition to the weak hip abductor status, a cross-sectional laboratory controlled study found that individuals with PFPS exhibit increased hip adduction angles toward the end of prolonged treadmill running compared to anthropometrically matched control individuals.²³ Significant associations are found between increased hip adduction angles and elevated knee abduction angles and torques in female, but not male, populations.³⁸ The elevated knee abduction loads during a dynamic task is a predictive variable for not only future PFPS development,⁹⁹ but non-contact anterior cruciate ligament injury in young female athletes.⁵⁵

Due to the influence of the proximal controllers to distal segments particularly in the frontal/coronal plane, recent studies focused on strengthening of hip musculature to improve knee joint mechanics. A randomized clinical controlled trial implemented two different exercise protocols (hip strengthening vs. quadriceps strengthening) to examine the effects of hip strengthening in the female population concluded that participants in the hip strengthening group had earlier pain relief compared to participants in the quadriceps group.²⁵ Another study that incorporated a series of proximal stability training aimed to enhance hip and core strength musculature and restore sound movement to a group of females with PFPS documented a 16.2 N.m less knee abduction moment in running after eight weeks.²⁹ Along with the alterations in

knee kinematics, the study also noted a considerable improvement in patient reported outcome scales including a visual analog scale and a Kujala anterior knee pain scale.

Significant evidence supports rehabilitative and prophylactic benefits of performing hip strengthening exercises on knee joint and related pathologies.^{25, 29} However, the threshold of training that is necessary to see treatment effects has not yet been determined. One potential measure for the training dosage is a compliance evaluation for a given intervention. Several studies examined compliance effects of neuromuscular training in female athletes and found significantly different injury rates based on different compliance levels.^{142, 149} One study found that female soccer players who practiced preventive neuromuscular training program with high compliance level reduced acute soccer injury incidence by 39% compared to those who participated in the same neuromuscular training program with intermediate compliance group.¹⁴² Another study also reported that low compliance level of neuromuscular training participation resulted in greater number of ACL injuries in female athletes.¹⁴⁹ In this study, female athletes who had low compliance to a given preventive neuromuscular training program demonstrated approximately five times greater rate of ACL injury compared to those athletes who recorded high compliance of neuromuscular training program.¹⁴⁹

Based on the prior reports, there appears to be an association between compliance level in neuromuscular training and athletic injury incidence. However, a missing link with this association is evidence of biomechanical and neuromuscular alterations. The high compliance to neuromuscular training may alter biomechanical and neuromuscular profile of athletes, which may be a mechanism that leads to lower rate of injury incidence. Concurrently, if the compliance level is low, biomechanical and neuromuscular alterations may not occur, which may be resulted in higher rate of injury incidence relative to athletes with high compliance. To our knowledge,

although the effectiveness of proximal neuromuscular training was reported,^{25, 29} the compliance effect of proximal neuromuscular training on muscular strength have not been reported. If a direct association between compliance level of proximal neuromuscular training and muscular strength is observed, it may potentially fill a gap to explain the different injury incidence rates based on the biomechanical and neuromuscular profile alteration. Therefore, the aim of the current project was to investigate the compliance effect of proximal neuromuscular training, a trunk and hip focused integrative neuromuscular training (INT), on isokinetic hip abductor strength in young female athletes. It was hypothesized that the female athletes who demonstrated the higher compliance to a trunk and hip focused INT would show a greater hip abductor strength enhancement.

Methods

Study Participants

A total of 21 adolescent age female volleyball players (height 171.5 ± 7.0 cm, weight 64.0 ± 7.4 kg, age 15.6 ± 1.4 years) were recruited from a local area high school. Because they were under 18 years old and considered minors, considered minors, signed informed consents were obtained from their parents or legal guardians prior to the beginning of this study. The informed consent forms were reviewed and approved by the institutional review board. Fourteen participants were assigned to participate in a trunk and hip focused INT program while seven participants served as a control group over a course of the study duration (Table 4.1).

Instrumentations

Hip abductor peak torque was assessed bilaterally using the Biodex 3 isokinetic dynamometer system (Biodex Medical System, Shirley, New York). The participants were

positioned to stand erect, facing the dynamometer head. The participants were then secured with a stabilization strap coming from across their waist above the iliac crest. The dynamometer head was aligned in parallel with the coronal plane of the subject's body with the axis of rotation of the dynamometer aligned with the center of rotation of the hip. The test limb was secured to the dynamometer head with a custom made hip attachment with the strap extending from the moving arm positioned immediately superior to the knee. The participants were instructed to grasp the top of the dynamometer head for support, minimize movement of the torso and abduct their leg with maximal effort. The isokinetic speed was set at 120°/second.

Testing Procedures

The participants visited the research laboratory as a team, and all participants were tested within two days during the team's off-season in April. Before the participants were actually tested, the participants performed 5-10 repetitions with submaximal effort for the purpose of warming-up and familiarizing with the test. Then, the participants were asked to perform five repetitions with maximum exertion. The sequence of the testing leg was stratified between the participants in order to control for a learning effect. A peak torque of the five maximum isokinetic hip abduction repetitions was extracted for statistical analysis. This procedure was repeatedly performed in post-testing sessions, which was performed at the end of the 10 week intervention in June.

Training Protocol

The fourteen participants in the intervention group were assigned to perform the trunk and hip focused INT program two times per week for 10 weeks. In addition to the 10 weeks of the trunk and hip focused INT program, the participants performed their standard sport related

resistance training protocol once a week. All participants' compliance was recorded by a researcher over a course of the study. For the compliance measurement, attendance and completion for the trunk and hip focused INT exercises were documented. When participants could not perform certain exercises because of injuries or time constraints such as leaving for other extra curriculum activities, being picked up by parent(s), or joining the INT session late, the trunk and hip focused INT session was marked as an incompleteness.

The INT exercises incorporated in the current study are described in a previously published study.⁹⁸ The objective of the INT was to enhance stability of trunk and hip in their dynamic movements through the progression of each exercise, and the progression was determined based on previous biomechanical studies.^{102, 103, 107} The initial phase of the INT program was adapted from previous studies^{58, 83, 110, 122} that demonstrated ACL injury reduction in female subjects. Only exercises that particularly emphasized trunk and hip regions were extracted because the INT was aimed to improve deficits in trunk control and improve hip strength and power in female athletes (Figure 4.1). Lateral trunk flexion deficits and increased ACL injury risk was reported by several studies in female athletes, but not in their male counterparts.^{59, 168} Thus, the INT purposefully incorporated exercises to improve the ability to control the trunk and hip from lateral perturbations at frontal/coronal plane.

Statistical Analysis

Descriptive statistics of the participants were performed. In order to analyze the compliance effect, three cohorts were created. The seven participants in the intervention group who demonstrated the highest compliance rate were classified in the high compliance group. The rest of the seven participants who had lower compliance rate in the intervention group were labeled as a moderate compliance group. The seven participants who did not perform the trunk

and hip focused INT remained as a control group. In order to examine the compliance effects on the hip abductor peak torque development, changed hip abductor peak torque values (post-testing values minus pre-testing values) were calculated, and one-way analysis of variance (ANOVA) was employed to find significantly difference hip abductor peak torque changes among the three compliance groups. When a statistical difference was detected, a post-hoc test (Bonferroni) was used to avoid type I error. Alpha level was set at 0.05 priori. Furthermore, a correlation coefficient value (r) was analyzed with the trunk and hip focused INT exercise compliance and the hip abductor peak torque changes to assess an association between the trunk and hip focused INT exercise compliance and the hip abductor peak torque changes. Assumption of linearity including outlier and normality was checked priori. Both analyses were performed using SPSS version 18 (SPSS, Inc, Chicago, IL 60606).

Results

All participants' data including mean and standard deviation of height, mass, age and pre- and post- hip abductor peak torque values were calculated (Table 4.1). The mean compliance rates of the high and moderate groups were 86.4% and 71.4% (Table 4.1). For the hip abductor peak torque changes, the participants in the high and moderate compliance group demonstrated 16.2% and 9.7% of increases; however the participants in the control group showed 1.1% decreases of hip abductor peak torque over the change of this study (Table 4.2).

One-way ANOVA indicated that there were statistical differences among the three compliance cohorts ($p = 0.02$). Post-hoc test (Bonferroni) detected that there was no significant hip abductor peak torque changes between the high compliance vs. moderate groups ($p = 0.27$) and moderate vs. control groups ($p = 0.68$) (Table 4.2). However, statistically different hip abductor peak torque changes were found between high and control groups ($p = 0.02$). The r

value between the hip abductor peak torque changes based on the three compliance groups recorded 0.56 (Figure 4.2).

Discussion

The purpose of this study was to investigate compliance effect of proximal neuromuscular training, a trunk and hip focused INT, on isokinetic hip abductor strength in young female athletes. The main finding of this study was that subjects in the moderate compliance group did not demonstrate significantly different hip abductor peak torque changes compared to control group (Table 4.2). On the other hand, those subjects who were labeled as a high compliance category showed significantly greater hip abductor peak torque changes relative to control group (Table 4.2). In addition, a moderate linear association was recorded between the hip abductor peak torque changes and the specific trunk and the three compliance groups (Figure 4.2). It can be interpreted that attending, performing, and completing the trunk and hip exercises are directly associated with greater increases in isokinetic hip abductor strength. Additionally, this information can be clinically translated to suggest that healthcare providers need to not only check patients' attendance for assigned treatment sessions, but also emphasize the importance of ensuring actual completion of exercises performed.

Several studies have intervened hip oriented neuromuscular training in female populations for the purpose of achieving hip abductor strength improvement.^{20, 25, 35} By implementing trunk and hip neuromuscular training in a young adult female population (N = 14, mean age = 20.7±1.7 years) for eight weeks, a study found an association between eccentric hip abductor strength and knee kinematic improvements.²⁰ The study reported increases of hip abductor strength of 9.7% in post-testing and decreases in knee abduction angles in the single leg

squat task.²⁰ Another study with a randomized cohort design that incorporated a set of hip exercises in females (N = 17, mean age = 25±5 years) with PFPS for eight weeks (hip oriented exercises were given in first four weeks) documented 21.0% of isometric hip abductor strength improvement.²⁵ Additionally, a study with adult female participants (N = 15, mean age = 35.2±12.2 years) with PFPS reported a 25.6% of isometric hip abductor strength increases (12.9 ± 4.1 % body weight (BW) at baseline, 17.1 ± 3.1 %BW at post-testing) as a result of three weeks of tubing band exercise intervention.³⁵ Although this study demonstrated a significant hip abductor strength increase, knee abduction angles, which were expressed as genu valgum in the original study, during treadmill running did not differ between pre- and post- intervention.³⁵

Compared to the current study, prior studies^{25,35} demonstrated greater relative hip abductor strength (21.0% and 25.6%) increases respectively. However, the association between participants' compliance and hip abductor strength gains was not clearly shown. From a compliance standpoint, the study gave participants an exercise log to check the home exercise compliance, but compliance information was not found in the original study.²⁵ In addition, Ferber and colleagues did not state any compliance information in the study; thus, it is difficult to compare the effect of the given intervention based on compliance alone. In Ferber's study,³⁵ which investigated dosage of the neuromuscular intervention (actual number of exercises performed as well as session length and frequency), the participants performed two types of tubing exercises that took 5 to 10 minutes daily for three weeks. Although the frequency of the intervention sessions was high (daily), the number of exercises performed, length of intervention session and duration of the study were the lowest among all investigations including the current study. However, this study demonstrated the greatest hip abductor strength increase (25.6%) compared to rest of the studies^{20,25} including the current study. In fact, the study²⁰ performed by

Baldon et al. incorporated more trunk and hip exercises than the Feber's study³⁵ and provided longer intervention sessions (90 minutes per session) and duration of study (eight weeks). The study set an inclusion criterion to a minimal compliance rate of participation at least 19 sessions out of 24 total sessions (80%).²⁰ The mean compliance rate of the study was 87% and no participants dropped out from this study due to the pre-determined compliance cut-off. However, the hip abductor strength increase was approximately 10% compared to the pre-value, which is much lower than the increases observed in Ferber's study.³⁵ In short, the hip abductor strength increases do not correspond to the given neuromuscular training dosage.

An underlying reason for the greater hip abductor strength gains in the prior studies^{25, 35} may stem from the type of the participants. The study performed by Ferber et al. had PFPS patients as a subject population.³⁵ Another study, that also used PFPS patients, showed a 21.0% hip abductor strength increase as a result of implementing eight weeks of rehabilitative exercises (a combination of four weeks of hip focused exercise and four weeks of functional weight bearing exercises).²⁵ However, the study performed by Baldon et al. that examined female individuals did not have a PFPS condition.²⁰ Recent clinical studies reported lower hip abductor strength in females with PFPS compared to females without PFPS.^{11, 18, 66} Therefore, the greater hip abductor strength increases observed in the two studies^{25, 35} may be primarily due to lower hip abductor strength baseline associated with the PFPS condition. In another words, females who have a lower hip abductor strength baseline are more responsive to hip focused neuromuscular exercises than females who already have an average or within normal level of hip abductor strength.

Because the current study demonstrated a strong association between trunk and hip focused INT compliance and isokinetic hip abductor strength changes, compliance is imperative

for those who have lower hip abductor strength such as females with PFPS. Yet, several previous studies struggled in achieving high neuromuscular compliance and noted it as a limitation.^{110, 146} In order to successfully incorporate neuromuscular training, the achievement of understanding and acceptance for the training from healthcare providers, coaching staff and each athlete was advocated.⁴¹ Additionally, it was stated that providing variety and progression to improve neuromuscular training may be a key to enhance neuromuscular training compliance. In the current study, a qualified instructor supervised every neuromuscular training session. The coaching staff members as well as the athletes were receptive of his instruction. Additionally, the INT program was designed to offer up to 13 diverse exercises per a session and was divided into five phases. Each of the INT exercises was individually progressed in phases by increasing the degree of difficulty. Each phase of the progressive INT was designed to bring more challenges, which was intended to enhance intensity of each exercise throughout the duration of the study. The wide variety of exercise selections and periodized progression may have assisted in maintaining 78.9% of compliance rates of the intervention group in this study.

Another interesting discussion point is how long the neuromuscular training effects can be retained. A study was conducted to test the retention of motor movement, which was approximately 15 minutes of balance training to female handball players.⁶² The balance training was given a minimum of three times per week in pre-season (five to seven weeks) and once a week during in-season (for approximately five months). This study found that the participants improved balance ability after eight weeks, and the gained balance ability was maintained approximately six months after completion of the program. Furthermore, a recent study evaluated motor learning retention ability of the lower extremity¹¹⁷ by implementing a 10- to 15-minute ACL prevention program three to four times per week. This study assessed jump landing

movement patterns in 14 years old girls and boys in two groups: three-months and nine-month durations. This study reported that the nine-month group retained the learned landing movement patterns for three months after post-ACL prevention training program whereas the landing movement patterns of the participants in the three month group returned to their original movements after three months. According to this result, it appears that a motor skill is better retained with higher dosage and longer duration training.¹¹⁷ Cumulatively, the current results add to the literature that there appears to be a certain threshold of exercise to influence the desired adaptations for injury risk reduction or reductions in symptoms. Future work focused on the dosage thresholds is warranted in helping guide future intervention design.

Limitations

The limitations to this study should be stated. The participants in the control group had higher hip abductor peak torque at pre-testing compared to the participants in the moderate and high compliance groups, which can be perceived as a confounding variable. However, in order to minimize the pre-testing value differences among groups, the change values, post-testing values minus pre-testing values, were used for the analysis. This needs to be addressed in future research. One aspect of neuromuscular training that would influence the magnitude of muscular strength development is intensity. Compliance and dosage (number of exercises, frequency and length of session and duration of intervention) can be measured objectively. However, it was challenging to measure a level of intensity from the participants although the qualified instructor (second author GDM who holds a certified strength and conditioning specialist certification) was present for every training session. Furthermore, concentric hip abductor strength measurements were taken instead of eccentric strength. Since ACL injury and PFPS pathologies occurred in closed kinetic chain motions, it was theorized that lower extremity muscles eccentrically

contracts.^{15, 113} Thus, an eccentric hip abductor muscle strength measurement was desirable instead of concentric hip abductor peak torque measures. Lastly, the participants in the intervention group performed routine strength training once a week in addition to the trunk and hip focused INT. Therefore, the routine strength training might have possibly contributed to the hip abductor peak torque changes.

Conclusion

A significant positive correlation was observed between the hip abductor strength improvement and the trunk and hip focused INT exercise compliance. The hip abductor strength improvement responses appeared to be directly related to the dosage of the specific trunk and hip focused INT. In comparison with other studies, it seems that hip abductor strength responses may be sensitive to a subject population. More specifically, the greater hip abductor strength gain may be obtained if the initial hip abductor strength has a deficit. Because those who have hip abductor strength deficit appear more responsive to neuromuscular training, participation and practice of the trunk and hip focused INT exercises are believed to be highly beneficial. Adaptations from trunk and hip focused training that improve hip abductor strength and recruitment may be protective against high knee abduction/valgus loading during dynamic movements, and potentially reduce ACL and PFPS risk in young female athletes. Future studies are warranted to include biomechanical measures and injury outcome data along with hip abductor strength changes.

Acknowledgements

I would like to show my deep appreciation to Dr. Myer for his tireless guidance, meaningful input and positive interaction throughout this project.

Table 4.1. Mean and standard deviation of the participants' height, weight, age and hip abductor peak torque values in pre- and post- testing.

	Control group (N=7)	Moderate compliance group (N=7)	High compliance group (N=7)
Height (cm)	173.4 ± 10.0	170.3 ± 5.0	171.6 ± 4.9
Weight (kg)	63.9 ± 5.3	59.4 ± 4.5	68.8 ± 8.3
Age (years)	16.0 ± 1.7	15.5 ± 1.4	15.5 ± 1.3
Compliance rate (%)	NA*	71.4 ± 3.8	86.4 ± 6.3

*Not applicable

Table 4.2. Mean and standard deviation of the participants' compliance rates, hip abductor peak torque values in pre- and post- testing.

	Control group (N=7)	Moderate compliance group (N=7)	High compliance group (N=7)
Hip abductor peak torque at pre-testing values (ft-lbs)	52.2 ± 10.4	46.4 ± 9.9	46.4 ± 10.4
Hip abductor peak torque at post-testing values (ft-lbs)	51.6 ± 6.1	51.4 ± 7.8	55.4 ± 13.1
Hip abductor peak torque changed values (ft-lbs)	-0.6 ^{a*}	+5.1 ^{ab}	+9.0 ^{b*}
Hip abductor peak torque changed values (%)	-1.1%	+9.7%	+16.2%

a The change value differences between control and moderate groups were not statistically significant. ($p = 0.68$)

b The change values differences between moderate and high groups were not statistically significant. ($p = 0.27$)

* The change value differences between the high and control groups were statistically significant. ($p = 0.02$)

Table 4.3. Effect size between control and moderate compliance groups on hip abductor peak torque changed values.

	Control group (N=7)	Moderate compliance group (N=7)	Effect size
Hip abductor peak torque changed values (ft-lbs)	-0.6 ± 7.2	+5.1± 4.9	0.9

Table 4.4. Effect size between control and high compliance groups on hip abductor peak torque changed value.

	Control group (N=7)	High compliance group (N=7)	Effect size
Hip abductor peak torque changed values (ft-lbs)	-0.6 ± 7.2	+9.0± 5.2	1.5

Figure 4.1. An example of the trunk and hip INT exercises (Kneeling trunk stability) and progression.¹¹

Phase 1. BOSU (round) double-knee hold

Phase 2. BOSU (round) single-knee hold

Phase 3. Swiss ball bilateral kneel

Phase 4. Swiss ball bilateral kneel with partner perturbations

Phase 5. Swiss ball bilateral kneel with lateral ball catch

Figure 4.1.

Phase 1.



Phase 2.



Phase 3.



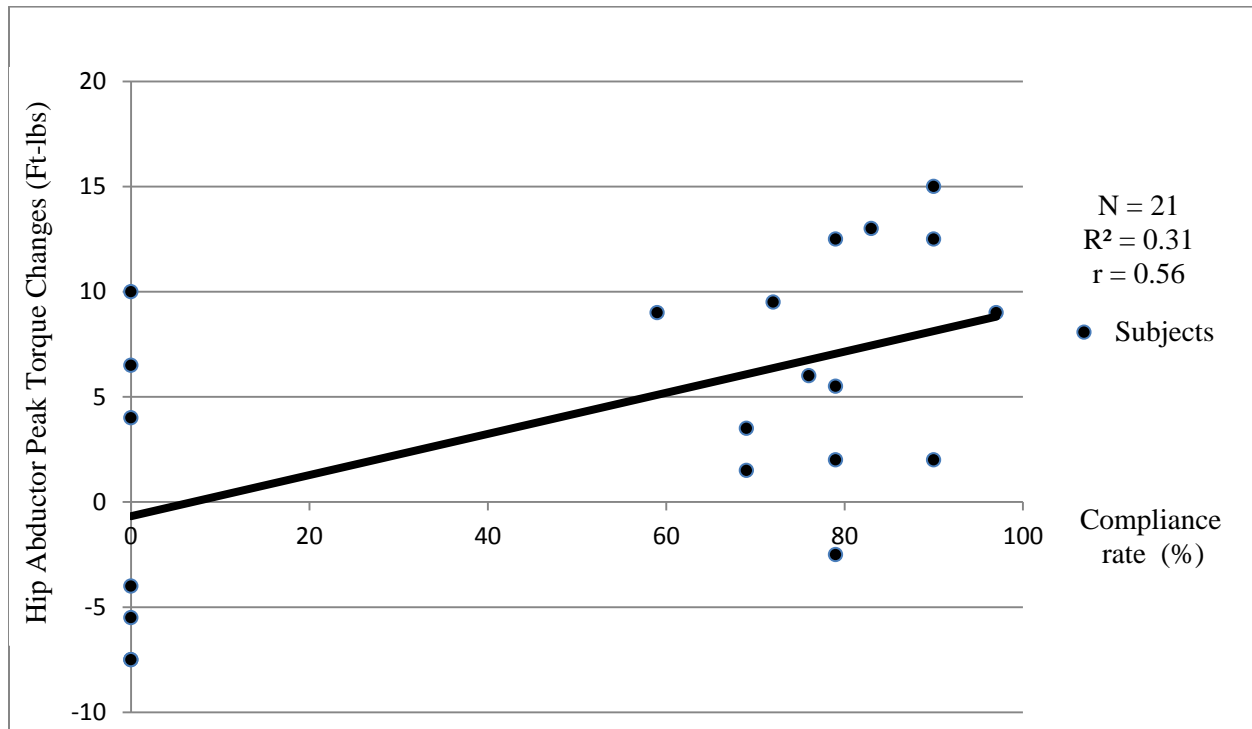
Phase 4.



Phase 5.



Figure 4.2. Correlation between a tertile categorization of the trunk and hip INT compliance and hip abductor peak torque changes. (N = 21)



Chapter 5 Effect of Compliance on Core Integrative Neuromuscular Training for Lower Extremity Musculature Strength in Female Athletes

Introduction

According to the National Collegiate Athletic Association (NCAA) injury surveillance system data, injury to the ACL increased by a rate of 1.3% over a 16-year time period.⁶⁴ As of 2007, it was estimated that approximately 250,000 ACL injuries occur annually in the US alone.¹³⁹ Those who suffered an ACL injury usually choose to have a reconstruction surgery, and the surgical costs are estimated as greater than \$18.7 billion over a 10-year period.⁶³

There is a disparity between sexes for who suffers an ACL injury. Female athletes have shown a higher susceptibility to knee joint injury, especially ACL injury.⁸⁸ For example, female soccer players have a 2-3 times higher ACL injury risk compared to their male counterparts.^{8,9,157} The total number of ACL injuries in female athletes was estimated to be approximately 38,000 annually in the US as of 2001.¹⁵¹ A similar trend was reported at the college level. Data from 1989 to 1998 demonstrated that female soccer and basketball players have 2.4 times and 4.1 times higher risk for suffering an ACL injury compared to their male counterparts in the same sports at the college level.⁹

It is theorized that ACL injury is multifactorial.^{5,47} Although the study of ACL injury risk factors have focused on anatomical, hormonal and neuromuscular factors, the neuromuscular components are one of the few if not only modifiable risk factor.⁵ In order to modify the ACL injury risk among female athletes, neuromuscular training (NMT) methods are often used as an intervention.^{43, 50, 53, 70, 73, 83, 110, 115, 120, 122, 125, 140, 146, 155} A wide variety of differences exist regarding type, length, frequency and duration of NMT in the literature. However, the majority of the studies demonstrated a reduction in ACL incidence rates in subjects in intervention groups when compared to those who were in control groups.^{43, 53, 70, 73, 83, 110, 115, 122, 146, 155} In fact, as of

May 5 2013, a total of 14 studies have been published that have included a NMT program with the purpose of lowering ACL incidence rates in young female athletic population.^{43, 50, 53, 70, 73, 83, 110, 115, 120, 122, 125, 140, 146, 155} Among the 14 studies, 10 studies documented lower ACL incidence rates for subjects in the intervention groups compared to subjects in control group.^{43, 53, 70, 73, 83, 110, 115, 122, 146, 155} Recent meta-analysis reports confirmed that NMT are effective to reduce a number of ACL injuries.^{42, 132}

In order to investigate the underlying mechanism of ACL injury reduction by NMT, several intervention studies focused on analyzing neuromuscular kinematic alterations after the NMT interventions.^{29, 58, 76, 77, 106, 107, 126, 20, 160} Among them, a few studies demonstrated reduced knee abduction moments^{58, 107} and angles^{106, 126} after NMT interventions. In addition, several studies reported greater knee flexion angles after the NMT programs.^{58, 77} Furthermore, several studies reported decreased ground reaction forces in landing tasks after the NMT interventions.^{58, 67, 76, 154} The aforementioned alterations in neuromuscular control variables are considered to provide a protective mechanism against ACL injury in female athletes. A study performed by Hewett et al. prospectively examined risk factors for ACL injury tracking 205 female high school athletes over 18 months.⁵⁵ Based on a comparison of biomechanical data between nine athletes who experienced an ACL injury and the 196 athletes who did not, the study concluded that elevated knee abduction moment, limited knee flexion, excessive ground reaction force and asymmetrical landing patterns can be used as predictive variables for the future ACL injury in female athletes.⁵⁵ Therefore, those neuromuscular alterations reported by the above NMT intervention studies are considered a prophylactic ally desirable modification.

Among those studies focusing on kinematic alteration by NMT, several studies documented the hip abductor, hamstrings and quadriceps muscular strength development in

female athletes. For example, one study that incorporated a series of exercises that consisted of 45 minutes of trunk and hip integrative NMT targeted to improve deficits in trunk control and hip strength and power reported a 13% and 17% improvement in isokinetic concentric hip abductor peak torque in the dominant and non-dominant legs in participants who trained two times per week for 10 weeks.⁹⁷ In another study, a series of tubing exercises were prescribed to a group of patients with PFPS for three weeks. The study demonstrated a 27% increase in isokinetic concentric hip abductor peak torque following the hip tubing exercise program.³⁵ In another study that assessed the effect of hip strengthening as a part of a rehabilitation program in young females with PFPS, a 21% increase in isokinetic concentric hip abductor peak torque following the training was reported.²⁵ Thus, it appeared that strengthening of the hip is attainable, important, and modifiable via a NMT in female athletes.^{25, 35, 97}

A few studies showed alterations in hamstrings and quadriceps peak torque following NMT interventions. A study that incorporated six weeks of plyometric exercises in a group of female high school athletes demonstrated 44% and 21% increases in isokinetic concentric hamstrings peak torque in the dominant and non-dominant legs as well as improvements of 26% and 13% of hamstrings:quadriceps peak torque ratio (H:Q ratio), respectively.⁵⁸ These findings are consistent in the literature. In fact, both concentric and eccentric quadriceps and hamstrings peak torque increases were reported following basic resistance, structured warm-up and hip and trunk stabilization NMT programs in middle school, high school and college athletes.^{20, 76, 77} In short, it appears that diverse NMT programs including plyometrics, basic resistance training exercises, and NMT programs that focused on functional movement patterns enhanced quadriceps and hamstrings torque and H:Q ratio changes.

For NMT intervention studies, compliance with the protocol is an important variable when determining success of the program and the usefulness of these programs for reduction of injury. However, the effect of compliance in NMT intervention studies is not well documented. Two studies, to our knowledge, measured the effect of NMT compliance on injury rates. Using a prospective cluster randomized controlled design, Soligard et al. examined the association between NMT intervention compliance and the number of injury incidence among young female soccer players.¹⁴² Compliance measures were analyzed from a total of 52 female soccer teams (a total of 1055 players) who participated in a comprehensive soccer specific warm-up program called “11 +”. Comparing overall soccer injuries based on the 11+ compliance rates using a tertile breakdown, those athletes who were defined as having high compliance showed a 35% lower overall injury incidence compared to athletes with intermediate compliance rates. Similarly, in terms of acute soccer injuries, athletes with high compliance experienced a 39% less injury incidence compared to athletes with intermediate compliance rates. The study concluded that the athletes with high compliance had a reduction of approximately one-third of overall and acute soccer related injuries during one soccer season while participating in the 11+ NMT interventions.

Another study compared ACL incidence rates among six NMT studies based on compliance rates.¹⁴⁹ The purpose of this study was to determine whether or not compliance of NMT plays a role in reducing the incidence of ACL injury in young female athletes, and compliance rates of six NMT studies were calculated based on athletes’ attendance and completed NMT sessions. The calculated compliance rates were compared to ACL incidence rates of each reviewed study. A binary incidence rate ratio analysis revealed that high compliance rate studies showed 73% lower ACL incidence rates compared to the low

compliance rate studies. Additionally, tertile incidence rate ratio analysis identified 82% lower ACL incidence rates with high compliance studies compared to moderate and lower compliance rate studies. Both analyses demonstrated the impact of the NMT compliance on ACL incidence rates.

Although two studies have been published regarding the effect of NMT compliance on injury incidence rates,^{142, 149} it must be noted that many of the papers in the analysis did not report their NMT compliance in the original manuscripts.^{32, 43, 83, 115, 122, 125, 158, 159} Furthermore, a few studies highlighted the importance of compliance, but did not document the rates.^{16, 83, 158} Also, several studies stated low NMT compliance as a limitation of the research experiment.^{110, 146} One study noted adequate compliance was recorded in only less than half of the study subjects and concluded that substantial compliance is necessary for observing true treatment effect.¹¹⁰ Another study also stated that NMT compliance was insufficient so that desirable NMT effect was not observed.¹⁴⁶

In short, reporting of compliance and the effect of NMT compliance are understudied, often neglected in analysis, and not emphasized in most study designs. There is no standard reporting method for compliance rate in NMT research, which may be a possible reason why compliance is often not reported. To our knowledge, no study has evaluated influence of NMT compliance effect on muscular strength. Therefore, the primary purpose of this study is to determine the effect of NMT compliance on hip abductor, hamstrings and quadriceps peak torque and H:Q ratio in young female athletes. There are three specific aims for this experiment:

1. To determine the effect of NMT on hip abductor, hamstrings, quadriceps peak torque and H:Q ratio between an intervention group (experimental core integrative NMT) and control group (control speed/agility NMT) of young female athletes. Hypothesis:

Subjects in the experimental core integrative NMT will demonstrate greater hip abductor, hamstrings, quadriceps peak torque and H:Q ratio when compared to subjects in a control speed/agility NMT group.

2. To compare the effect of NMT compliance on hip abductor, hamstrings and quadriceps peak torque and H:Q ratio in young female athletes of experimental core integrative NMT group. Hypothesis: Greater hip abductor, hamstrings and quadriceps peak torque and H:Q ratio changes will be observed in groups with higher NMT compliance rates compared to lower NMT compliance groups in the experimental core integrative NMT group.
3. To determine the number of NMT sessions to lead to optimal hip abductor peak torque and H:Q ratio in the experimental core integrative NMT group. Hypothesis: There is an identifiable number of NMT sessions that demonstrate optimal hip abductor peak torque and H:Q ratio.

Methods

Study Design

A prospective cluster randomized controlled trial design was employed. The clusters were girls' soccer, volleyball and basketball teams in middle and high schools in the greater Cincinnati area. Each team was randomly assigned to either an intervention group (experimental core integrative NMT) or control group (control speed/agility NMT). The randomization was performed independently by a statistician who maintained the concealment so that all other research team members associated with the project including the principal investigator, outcome assessors, laboratory assistants and intervention providers were blinded from beginning of the

trial to the middle of the data analysis. Additionally, the current trial followed an intention to treat (ITT) protocol. The ITT assured that none of the subjects was excluded once it was randomized.⁶¹ The purpose of the ITT is to preserve the random allocation of the trial³⁶ and avoid bias associated with nonrandom loss of participants.⁹¹ The randomization code was maintained for more than three years and revealed to the investigators on October 1, 2012.

Subjects

Parents, legal guardians, and coaches from a total of 54 teams, which consisted of female soccer (27 teams), soccer (11 teams) and basketball teams (18 teams) at public middle and high schools in the greater Cincinnati area agreed to participate in this study. Coaches were contacted via telephone and US postal service under approval of the Boone county public school system's approval and asked to participate in the study. Once agreement from the coaches was received, assent forms were signed by each subjects' parents or legal guardians and collected prior to participation. Coaches and subjects were blinded to the specifics of the NMT program in which they participated throughout a course of this trial.

Laboratory Assessment

Each team attended a pre-testing session prior to initiation of the assigned NMT intervention and subsequent hip, hamstrings and quadriceps isokinetic strength tests. The strength assessment procedure was again performed in a post-testing session.

Instrumentation for Isokinetic Tests

Bilateral isokinetic concentric hip adductor peak torque was evaluated using the Biodex System 3 Isokinetic dynamometer (Biodex Medical System, Shirley, New York). Gravity

correction was not performed because of limited time availability of each subject. The isokinetic speed was set at 120°/second. Similarly, bilateral isokinetic concentric hip flexion and extension torque were measured by the Biodex system 2 Isokinetic dynamometer (Biodex Medical System, Shirley, New York). Gravity correction was performed, and the isokinetic speed was set at 300°/second.

Testing Procedures for Isokinetic Hip Abductor Strength

Subjects were tested in a standing position. The subject stood facing the dynamometer with the hip joint axis of rotation aligned with the dynamometer axis of rotation in the frontal plane (Figure 1). The hip joint axis of rotation was defined as the intersection of an imaginary line directed inferiorly from the anterior superior iliac spine down the midline of the thigh and a second imaginary line medially directed from the greater trochanter of the femur toward the midline of the body. An attachment arm was placed over the middle one-third of the lateral thigh and resistance pad was applied at the same level of the medial thigh. The hip was securely restrained by a supporting strap to stabilize hip and torso movements during testing.

Each subject was given a brief explanation of the task and several pre-trial submaximal repetitions before performing the actual trial. For the trial, subjects were asked to “pull out” their limb to the side (hip abduction direction) as hard and fast as possible. Once the limb reached approximately a 45° angle, the subjects were instructed to relax and bring the limb to the original standing position. The subjects initiated testing following a verbal start command from the tester, and verbal encouragement was given to the subjects throughout the testing session to employ maximal efforts. A total of five repetitions were performed per limb. After one limb was tested, the subjects received a few minutes of rest to prevent muscular fatigue of the contralateral hip as pelvic stabilization during this activity results in bilateral co-contraction of the hip musculature.

The same process was repeated with the opposite limb. Testing order for each limb was counterbalanced throughout.

Testing Procedures for Isokinetic Hamstrings and Quadriceps Strength

The subjects were tested in a seated position. The start position was 90° of knee flexion. The subjects' knee joint axis was aligned with the dynamometer axis of rotation of the sagittal plane (Figure 2). The knee joint axis of rotation was defined as the position of the joint line between distal femur and proximal tibia. An attachment arm was placed over distal one-third of the posterior calf and a resistance pad was applied at the same level of the frontal side of calf. The thigh was securely restrained by a supporting strap to stabilize thigh and hip movements during testing. Additionally, subjects were asked to place their hands on the side of the seat during testing to minimize torso movement.

Each subject was given a brief explanation of the testing and several pre-trial submaximal repetitions were performed before the actual trials. Subjects were asked to “push” their limb to the front (knee extension direction) as hard and fast as possible. Once the limb reached approximately a 180° angle (straight knee position), the subjects were instructed to pull the limb to the rear (knee flexion direction as hard and fast as possible. The subjects initiated testing following a verbal start command from the tester, and verbal encouragement was given to the subjects throughout the testing session to employ maximal efforts. A total of ten repetitions were performed per limb. After one limb was tested, the opposite limb was tested subsequently with the same process. Testing order for each limb was counterbalanced.

Training Protocol

Both interventions were initiated at pre-season and continued until the end of the sport seasons that included the period of play-offs, respectively. The individuals providing the allocated NMT intervention consisted of the coaching staff, certified athletic trainers, or undergraduate college students who were in sports medicine associated degrees. All intervention providers attended a mandatory education and training session prior to their intervention. The education and training sessions for intervention providers took place separately based on the assigned intervention (experimental core integrative vs. control speed/agility) NMT programs in order to maintain blinding among the intervention providers.

For the core integrative NMT, a series of exercises, which were designed to target trunk stabilization and improve hip strength and power, were performed by the subjects in the core integrative NMT group. The exercises for this group were derived from previous studies that had demonstrated success such as decreased incidence rates and altered neuromuscular control following their use.^{58, 83, 97, 110, 122} The prophylactic neuromuscular control alterations that were reported included; less knee abduction moment,^{29, 76, 77} knee abduction angles,^{20, 160} and greater knee flexion angles^{58, 76, 77} in dynamic tasks.

The core integrative NMT focused on developing trunk stability, improving hip strength and power and mastering sound landing technique. The core integrative NMT exercises' level of intensity, difficulty and techniques were progressed throughout the season. The intervention providers were asked to practice the core integrative NMT 15-30 minutes three times per week during pre-season. Once teams began the in-season regimen, the duration and frequency of the core integrative NMT was shortened to 10-15 minutes two times per week.

The protocol of the duration and frequency for the control speed/agility NMT were the same as that the core integrative NMT program. The control speed/agility NMT used a rubber

band (Jump Strength Inc., Youngstown, OH), which was secured around the subjects' trunks to provide resistance. Then, the subjects were asked to run forward and backward while tension was placed on the rubber band to provide resistance (Figure 3). This purported purpose of this training method was to enhance sprint start speed and increase stride frequency in young female athletes.¹⁰¹

Compliance Tracking

Upon completion of the education and training sessions, each intervention provider received a booklet from a study coordinator. The booklet listed the name of the team roster, a list of assigned exercises and repetitions and sets of each exercise. Each of the assigned exercises were illustrated in the booklet. In addition to the description of the assigned exercises, each intervention provider received a mini portable laptop, which contained a demonstration of all exercises with short video format demonstrating correct and incorrect examples of technique.

The intervention providers were asked to take each subject's attendance and document the completion of exercises for each subject at the end of each session. If a subject did not finish the assigned exercises in a session, we defined this as not being compliant for that session. The study coordinator contacted each intervention provider weekly and collected the compliance information through electronic mail using an excel spread sheet attachment. When the compliance information was not obtained, a subsequent request was made to intervention provider by the study coordinator.

Definition of Compliance Calculation

One of the research associates contacted a member of the coaching staff weekly to find how many practices were carried out in each week during their seasons. The compliance rate

calculation started from the first NMT session of the season and continued throughout the last NMT session of the seasons. After end of the regular season, several teams qualified to participate in a play-off, which yielded more opportunities to perform NMT. In order to standardize the time point measures across the included teams, the number of NMT sessions performed during the play-off was excluded in the current analysis.

Individual compliance was selected since it was believed to be the most reflective variable of NMT activity engagement. The individual compliance calculation is described in Table 1. The following definition was used for the individual compliance calculation:

- Individual compliance = Summation of a NMT sessions that individuals on roster attended and completed.

Data Analysis

The compliance was analyzed by binary and tertile methods. For the binary comparison, the high compliance and low compliance groups were defined as follows:

- High compliance group=Individuals that demonstrated greater than 50.0% of individual compliance.
- Low compliance group=Individuals that demonstrated less than 50.0% of individual compliance.

For the tertile comparison, the compliance was classified by the following three categories:

- High compliance group=Individuals that demonstrated greater than 66.6% of individual compliance.

- Moderate compliance group=Individuals that demonstrated between 66.6% and 33.3% of individual compliance.
- Low compliance group=Individuals that demonstrated less than 33.3% of individual compliance.

Dependent and Independent Variables

The independent variable for specific aim 1 was an intervention. The intervention group was assigned to perform a core integrative NMT, and the control group performed a speed/agility NMT. For the specific aim 2, the independent variable was compliance sub-groups within the experimental core integrative NMT group. In the binary analysis, the independent variables were high and low compliance groups in the experimental core integrative NMT. In the tertile analysis, the independent variables were high, moderate, and low compliance groups in the experimental core integrative NMT. For the specific aim 3, the independent variables were hip abductor peak torque and H:Q ratio in the experimental core integrative NMT. The dependent variables were hip abductor, hamstrings and quadriceps peak torque and H:Q ratio changes for the specific aim 1 and 2. For the specific aim 3, the dependent variable was a number of core integrative NMT sessions. The highest peak torque value from the five isokinetic hip abductor, hamstrings and quadriceps strength tests were extracted for the analysis.

The H:Q ratio was calculated as hamstrings peak torque divided by quadriceps peak torque values. The greater H:Q ratio scores indicates higher hamstrings peak torque relative to quadriceps peak torque. It was theorized that stronger hamstrings strength is important for ACL injury prevention because they prevent the tibia from moving forward during dynamic movements and thus reduce ACL loading.^{100, 165}

Statistical Analysis

All teams were randomized to receive either an experimental core integrative or control speed/agility NMT programs so it was assumed that the randomization would make groups similar for: age, height, weight, BMI, pubertal status, school levels, and pre-intervention strength levels for hip abductor, hamstrings, quadriceps and H:Q ratio. However, the sample size was relatively small (N=56) and the randomization may not equalize both groups on all confounding variables. Therefore, the experimental core integrative and control speed/agility NMT groups were compared for any potential confounders including the primary dependent variables. Demographic and all potential confounding variables were analyzed using descriptive statistics prior to the analyses for specific aim 1 and 2.

Specific aim 1 was to determine the effect of NMT on hip abductor, hamstrings, quadriceps peak torque and H:Q ratio between an experimental core integrative NMT and control speed/agility NMT groups of young female athletes. Characteristics of subjects in each group (experimental core integrative vs. control speed/agility) were compared with descriptive statistics and an independent sample t-test. Pre-intervention strength values between the experimental core integrative and control speed/agility NMT groups were also compared by an independent t-test. Although the randomization was performed, the number of teams (N=56) was relatively small. Thus, variables, which were statistically different between the experimental core integrative and control speed/agility NMT programs were treated as covariates. The change values, post-intervention values minus pre-testing values, were calculated and used as dependent variables to avoid baseline differences of each dependent variable. The dependent variables were the change values of hip abductor, hamstrings, quadriceps peak torque and H:Q ratio. The

change values of hip abductor, hamstrings and quadriceps peak torque and H:Q ratio were analyzed by an analysis of covariance (ANCOVA). The alpha level was set < 0.05 priori.

To test specific aim 2, subjects in an experimental core integrative NMT group were classified in a compliance sub-groups by binary and tertile categorizations. (low and high under the binary analysis; low, moderate, and high under the tertile analysis) For the binary analysis, characteristics of subjects in the compliance sub-groups were compared by descriptive statistics and independent t-test. For the tertile analysis, descriptive statistics and one-way analysis of variance (ANOVA) were employed to detect statistical differences among the compliance sub-groups. When statistical differences were found, Bonferroni correction was used as a post-hoc analysis to avoid type I error. Also, pre-intervention strength values in the compliance sub-groups within the experimental core integrative NMT were analyzed by an independent t-test for binary analysis and one-way ANOVA for the tertile analysis. Bonferroni correction was performed when significant differences were found. Variables that were statistically different among the compliance sub-groups in the descriptive and pre-intervention strength analyses were treated as covariates and incorporated with the subsequent ANCOVA analysis. ANCOVA was applied to compare the compliance sub-groups within the experimental core integrative NMT for each dependent variable (hip abductor, hamstrings, quadriceps peak torque and H:Q ratio). The alpha level of the ANCOVA was set at < 0.05 priori.

To determine specific aim 3, a receiver operating characteristic (ROC) curve analysis was employed to examine a number of NMT sessions that lead to optimal hip abductor peak torque and H:Q ratio in the experimental core integrative NMT group. The optimal hip abductor peak torque and H:Q ratio were determined by previous literature that identified muscular strength deficits and potential risk for future injury.^{65, 75 100} One study documented that an ACL injured

female athlete had one standard deviation lower hip abductor peak torque compared to uninjured female athletes.⁷⁵ Thus, the cut-off values for the optimal hip abductor peak torque values were determined as one standard deviation lower than a mean hip abductor peak torque values. Another study reported H:Q ratio differences between 16 female athletes who tore ACL and 88 female athletes did not tear ACL.¹⁰⁰ A mean H:Q ratio of eighty-eight female athletes who did not tear ACL was greater than 0.6; however, a mean H:Q ratio of the 16 female athletes who tore ACL were less than 0.6.¹⁰⁰ Therefore, the H:Q ratio cut-off values were determined as 0.6. Area under curve values, 95% confidence intervals (CIs), and asymptotic significance values were noted. To identify the most applicable number of the experimental core integrative NMT sessions for hip abductor peak torque and H:Q ratio, a point, which maximized sensitivity and minimized false-positive rate (1-Specificity), was determined via visual inspection. Sensitivity, false-positive rate, and positive likelihood ratio were also analyzed.

Results

Specific Aim 1 – Comparison between Experimental and Control Groups

A total of 56 teams were enrolled in this research project. Before the enrolled teams were randomly allocated to either experimental core integrative or control speed/agility NMT group, 73 subjects were excluded because they were cut from their teams and did not make a team roster. Additionally, four subjects declined to perform the isokinetic tests. Therefore, 77 subjects were excluded before the randomization (Figure 4). A total of 34 teams (14 basketball, 6 soccer and 14 volleyball teams) were assigned for the experimental core integrative NMT group whereas 22 teams (13 basketball, 5 soccer and 4 volleyball teams) were allocated into the control speed/agility NMT group (Figure 4). During this clinical trial, approximately 110 subjects were lost to follow-up. The majority of the lost subjects did not show up for the post-testing session

including one soccer team (Figure 4). As a result the dropout rate of the subjects was approximately 20%.

Demographic Descriptive Statistics between Experimental and Control Groups

Demographic descriptive statistics between the experimental core integrative NMT and control speed/agility NMT groups can be found in Table 2. There were no significant differences for height, weight, BMI and age when the experimental core integrative NMT and control speed/agility NMT groups were compared. However, there were significant differences in number of pre-season practices, number of in-season practices, number of competitions, team compliance during in-season, and team compliance during entire season when the experimental core integrative NMT and control speed/agility NMT groups were compared (Table 2). The number of pre-season practices and number of competitions were higher in the control speed/agility NMT group whereas the number of in-season practices was greater in the experimental core integrative NMT group.

Pre-intervention Strength Values between Experimental and Control Groups

Pre-intervention strength values between the experimental core integrative NMT and control speed/agility NMT groups are presented in Table 3. There were no significant differences in pre-intervention strength values of bilateral hip abductors, bilateral hamstrings, bilateral quadriceps and left H:Q ratio between the experimental core integrative NMT and control speed/agility NMT groups (Table 3). However, there was a significant difference between the experimental core integrative NMT and control speed/agility NMT groups for right H:Q ratio (Table 3).

Specific Aim 1 – Results of Comparisons between Experimental and Control Groups

Those variables that were different between the experimental core integrative and control speed/agility NMT groups were incorporated in the ANCOVA as covariates. Then, change values of hip abductor, hamstrings, quadriceps peak torque and H:Q ratio were analyzed by an ANCOVA. There were no differences for hip abductors, hamstrings, quadriceps peak torque and H:Q ratio between the groups (Table 4).

Specific Aim 2 – Binary Compliance Comparison within Experimental Group

Demographic Descriptive Statistics between High and Low Compliance Groups

Subject allocation of binary analysis was described in Figure 5. Subjects who participated in the experimental core integrative NMT intervention less than 15 sessions were categorized in a low compliance group, and those who participated in the experimental core integrative NMT intervention more than 16 sessions were classified into a high compliance group. Description of subjects between the high and low compliance groups is displayed in Table 5. There were significant differences in height, weight and age in subjects between the high and low compliance groups (Table 5). Subjects in the high compliance group were taller, heavier and older than subjects in high low group. Additionally, the number of pre-season practices and number of in-season practices were significantly different (Table 5). The number of pre-season practices and number of in-season practices were higher in the high compliance group compared to low compliance group. Also, the number of pre-season exercises, the number of in-season exercises and the number of exercises in the entire season were different between the high and low compliance groups, and high compliance group performed significantly greater number of exercises.

Pre-intervention Strength Values between High and Low Compliance Groups

Pre-intervention strength values between the high and low compliance groups are presented in Table 6. There were no significant differences in pre-intervention strength values of bilateral hip abductors and bilateral hamstrings between the groups (Table 6). However, there were statistically significant differences in bilateral quadriceps and H:Q ratio between the high and low compliance groups (Table 6). The high compliance group had greater bilateral quadriceps peak torque and lower H:Q ratio compared to low compliance group (Table 6).

Specific Aim 2 – Results of Binary Compliance Comparison

Those variables that were statistically different between the high and low compliance groups were incorporated in the ANCOVA as covariates. No statistical significance was found in bilateral hip abductors, bilateral quadriceps, right hamstrings and bilateral H:Q ratio between the high and low compliance groups (Table 7). However, there was a significant difference for left hamstrings peak torque between the high and low compliance groups (Table 7). The high compliance group demonstrated greater left hamstring peak torque compared to the low compliance group.

Specific Aim 2 – Tertile Compliance Comparison within Experimental Group

Demographic Descriptive Statistics between High, Moderate and Low Compliance Groups

Subject allocation of tertile analysis is illustrated in Figure 6. Subjects who participated in the experimental core integrative NMT intervention less than 10 sessions were categorized in a low compliance group. Subjects who practiced the experimental core integrative NMT intervention between 11 and 20 sessions were classified into a moderate compliance group, and subjects participated in the experimental core integrative NMT intervention greater than 21 sessions were categorized in a high compliance group. Demographic descriptive statistics

between the high, moderate and low compliance groups are presented in Table 8. Significant differences in age, height, weight, and BMI were found in subjects among the high, moderate and low compliance group (Table 8). Subjects in the high compliance group were taller, heavier and older than subjects in the moderate and low compliance groups. Similarly, the height, weight, and age in the moderate compliance group were greater compared to the low compliance group. Additionally, the number of pre-season practices and number of in-season practices were different among the three compliance groups (Table 8). The number of pre-season practices was the highest in the moderate compliance group whereas the number of in-season practices was the greatest in the high compliance group compared to rest of the compliance groups. The number of pre-season exercises, in-season exercises and number of exercises in the entire season were significantly different among the compliance groups. The greatest numbers of exercises performed during pre-, in- and entire seasons were recorded in the high compliance group when compared to the moderate and low compliance groups (Table 8).

Pre-intervention Strength Values between High, Moderate and Low Compliance Groups

There were significant differences in the pre-intervention strength values of bilateral hip abductors, bilateral hamstrings, bilateral quadriceps, and bilateral H:Q ratio among the high, moderate and low compliance groups (Table 9). The pre-intervention strength in high compliance group was greater than the low and moderate compliance groups in left hip abductor. In right hamstrings, pre-intervention strength in the high compliance group was greater than the moderate compliance group. In right quadriceps, pre-intervention strength of high compliance group was greater than the low compliance group. In left quadriceps, pre-intervention strength of high compliance group was greater than the low compliance group. In both right and left H:Q ratio, pre-intervention strength was statistically different between low compliance and moderate

compliance groups and between low compliance and high compliance groups, but not between moderate and high compliance groups.

Specific Aim 2 – Results of Tertile Compliance Comparison

Based on the descriptive statistics and pre-intervention strength value differences among the three compliance groups, covariates were carefully selected, and those selected covariates were incorporated in the ANCOVA. No statistical significance was found in bilateral hip abductors, right hamstrings, right quadriceps and right H:Q ratio among the three compliance groups (Table 10). However, there were significant differences in left hamstrings, left quadriceps and left H:Q ratio (Table 10). There were significant differences between low and moderate compliance and low and high compliance groups in left hamstrings. For the H:Q ratio, there were significant difference between low and moderate compliance groups (Table 10).

Specific Aim 3 – Results of ROC Curve Analysis based on Binary Compliance Comparison

Results of the ROC curve analysis including area under the curve, 95% CIs, and asymptotic significance values can be found in Table 11. From the previous literature,^{75, 100} the optimal hip abductor peak torque cut-off value was determined as one standard deviation lower than a mean hip abductor peak torque value,⁷⁵ which was 41.68 Nm and 39.82 Nm for the right and left hip abductor. Also, the optimal H:Q ratio cut-off values were set at 0.6 for both right and left H:Q ratio based on previous literature.¹⁰⁰ Figure 7-10 depict the ROC curves associated with subjects in the core integrative NMT group. For both right and left hip abductor, there was no difference in individual compliance between subjects who had greater than the cut-off values (41.68 Nm for right and 39.82 Nm for left) and those who had less hip abductor cut-off values (Table 11; Figure 7 - 8). In left H:Q ratio, there was no difference in individual compliance

between those who had greater than 0.6 H:Q ratio and those who had less than 0.6 H:Q ratio (Table 11; Figure 10); however, there was a significant difference in individual compliance rate in right H:Q ratio (Table 11; Figure 9). The area under the curve for the right H:Q ratio was .600 (95% CIs: 0.533, 0.668; Figure 9), and the identified core integrative NMT session number was 28.5.

Discussion

The primary findings of our study were that strength of hip abductors, hamstrings and quadriceps did not differ between the experimental core integrative and control speed/agility NMT groups. There were no decreased values recorded for the peak torque values for all of the hip musculature in both groups. Therefore, it can be concluded that peak torque of hip abductors, hamstrings, and quadriceps from both groups did not change over the course of the study (Table 4). Negative values were recorded in the H:Q ratio, which can be translated that quadriceps strength was greater compared to hamstrings strength. More specifically, it appeared that quadriceps strength increased to a greater extent than that which occurred in the hamstring muscle group in the experimental core integrative group (Table 4). However, subjects in the control speed/agility NMT group had greater hamstrings strength development relative to quadriceps strength on left leg, but not right. In general, there were no significant hip musculature strength differences between the experimental core integrative and control speed/agility NMT groups.

A potential explanation for the lack of a strength change observed in this study may stem from the duration of the experimental core integrative NMT program session. In comparison, in a study that incorporated a core integrative NMT with female high school volleyball players, there were 13.5% and 17.1% increases in hip abductor peak torque in the dominant and non-dominant

leg.⁹⁷ Compared to our study, recorded hip abductor strength increases in this study were 2.2% for both right and left legs, respectively. The disparity of the strength development may be explained by different durations of the intervention session. The female high school volleyball players who demonstrated over 13.5% and 17.1% of dominant and non-dominant hip abductor strength changes spent 20 to 40 minutes per session in the training.⁹⁷ The protocol of this project was to perform the core integrative intervention in 15-30 minutes during pre-season and 10-15 minutes during in-season. The time spent for the core integrative NMT intervention was relatively shorter in this study compared to the study performed by Myer et al. More specifically, the time spent for the core integrative NMT was approximately two times greater in the study done by Myer et al.⁹⁷ compared to the current study. If the NMT session duration was longer, greater numbers of exercises would have been performed, which may have generated greater strength gains.

In comparison to other literature, one study reported similar findings as us. In the study by Steffen et al., there were no changes in muscular strength after implementing an ACL prevention NMT in female soccer players.¹⁴⁵ Specifically, the study by Steffen et al. assessed hip musculature development from 18 female soccer players who performed the “11” preventive NMT program three times per week for 10 weeks. There were no significant differences in isometric hip abductor, isometric adductor, isokinetic hamstrings and isokinetic quadriceps peak torque changes compared to 17 female soccer players in the control group.¹⁴⁵ The author concluded that the “11” preventive NMT program was designed to prevent traumatic knee injuries so that the volume and intensity of the exercises were too low to improve muscular development.¹⁴⁵ Interestingly, hip musculature strength increases were found in another study that instituted a modified PEP (Prevent injury and Enhance Performance) NMT program.⁷⁷ The

modified PEP NMT program, focused on prevention of injury as well as performance enhancement, and was performed for 20 minutes in every warm-up for eight weeks. The results were that 11 female high school basketball players demonstrated 11.7% increases in isokinetic hip abductor peak torque, 9.8% increases in hamstrings peak torque, and 29.4% increases in quadriceps peak torque compared to pre-testing values. Also, the strength gain in the hip abductors, hamstrings and quadriceps were significantly different from 11 female high school basketball players who served as a control and maintained their regular routine practices.⁷⁷ The differences between the two studies of Steffen and Lim can be linked to repetitions and number of exercises performed. In the study conducted by Steffen, Russian hamstring curl was prescribed for five repetitions compared to 30 repetitions in the study done by Lim.^{77, 145} Also, there were three types of plyometrics in Steffen's study, but five plyometric exercises were performed in Lim's study. In our study protocol, approximately three to four types of plyometric exercises in each core integrative NMT session, and each plyometric exercise were performed for 16-20 repetitions. Some plyometric exercises such as the tuck jump and lunge jumps were performed based on a time duration of 10 seconds instead of repetitions. It was estimated that five to eight jumps can be performed during the 10 second duration. The total number of plyometric repetitions in this study protocol was not as high as the plyometric repetitions reported by the Lim's study. In Lim's study, 20 repetitions were performed in each plyometric exercise,⁷⁷ and the total number of plyometric repetitions were 150 compared to our study, which ranged from 53 to 128. In short, the lower number of plyometric repetitions may have contributed to minimum hip musculature development in this study.

An important consideration is whether increased plyometric repetitions lead to strength increases in type I (slow-twitch) or type II (fast-twitch) muscle fibers because the increased

number of repetitions may be stimulating type I (slow-twitch) muscle fibers. For instance, in our study, tuck jumps were executed in 10 seconds, which is considered anaerobic in nature, and muscular fibers used for anaerobic exercises were type II (fast-twitch fibers). However, some plyometric exercises incorporated in our study were practiced repetitions, which usually took longer than 10 seconds. Because the time duration exceeds longer than 10 seconds and multiple exercises were performed, it is unclear if the musculature development is from type I (slow-twitch) or type II (fast-twitch) muscle fibers. This issue was particularly imperative since our musculature strength test protocol for hip abductor, hamstrings, and quadriceps were usually performed under 10 seconds. To clarify this issue, one recent study extracted blood and muscle sample from individuals who finished performing a bout of plyometric exercises.⁸¹ In this study, 10 sets of 10 squat-jumps were performed by eight young adults, and 1 minute of rest was given between each set. A post-analysis of blood and muscle samples recorded that muscular damage was more prevalent in type II (fast-twitch) muscle fibers compared to type I (slow-twitch) muscle fibers.⁸¹ The plyometric exercises instituted in this study was shorter than the aforementioned study. Thus, it is a reasonable assumption that plyometric exercises incorporated in our study likely predominantly stimulated type II (fast-twitch) muscle fibers.

Plyometric exercises incorporated in our study likely stimulated type II (fast-twitch) muscle fibers; however, the session length and number of repetitions were shorter and lower compared to previous studies,^{77, 97} which may potentially explain the reason why there was no difference in hip musculature between the experimental core integrative and control speed/agility groups. An additional explanation may be a lack of strengthening exercises in the experimental core integrative NMT program. A recent study reviewed 15 NMT intervention studies and documented that a combination of plyometrics and strengthening exercises likely optimize

strength enhancement.¹³³ In our study protocol, three to four types of plyometric exercises were incorporated in each session; however, instead of strengthening lower extremity musculature, the current study focused on targeting trunk stabilization and improved hip strength and power. The rationale for this protocol was instituted because a connection between decreased trunk control and increased ACL injury risk was reported by two previously published studies.^{59, 167} Additionally, there is a biomechanical association between hamstrings and trunk in dynamic movement.^{71, 72} A study reported greater hamstring force generation in trunk flexion condition compared to trunk extension condition.⁷² Also, it was documented that increased trunk flexion decreases knee joint moment in single leg landing task^{127, 136} as well as actual ACL strain in a single leg tasks.⁷¹ Therefore, in each session, there were four to six core and trunk musculature strengthening and stabilizing exercises instead of hip abductor, hamstrings and quadriceps strengthening. In Lim's study, there were three lower extremity strengthening exercises along with five plyometric exercises. Hence, the reason why the current study did not document strength increases in hip abductor, hamstrings and quadriceps may stem from a lack of strengthening exercises of lower extremity.

Our findings support an important clinical question; is muscular strength improvement necessary to prevent injury? The aforementioned study conducted by Lim et al. that investigated the effects of a modified PEP program, which consisted of three warm-up running activities, five stretching techniques, three strengthening exercises, five plyometric exercises and three agility drills, showed 11.7% increases in isokinetic hip abductor peak torque, 9.8% increases in hamstrings peak torque, and 29.4% increases in quadriceps peak torque.⁷⁷ Another study implemented a 120 minutes of structured stretching, strengthening and jump training for three times per week for six weeks to 11 healthy female high school volleyball players. They reported

that peak torque of the hamstrings increased 44% and 21% in the dominant and non-dominant limbs, which further led to 26% and 13% H:Q ratio increases for the dominant and non-dominant limbs.⁵⁸ Both studies reported prophylactic effectiveness of NMT interventions through ACL injury reduction in female athletes, which can be interpreted that the prophylactic effectiveness of NMT on ACL injury was generated from strength increases of lower extremities. Furthermore, to support importance of muscular strength, the study implemented “11” preventive NMT program did not only record hip muscular strength increases, but the prophylactic effects on ACL injury reduction was not strong.¹⁴⁶ However, a study that just provided a video instruction training in alpine skiing patrollers and instructors documented significant ACL injury reduction compared to previous years and control group.³³ This study did not incorporate any NMT intervention for the subjects in the experimental group, yet documented significant ACL injury reduction, which can be interpreted that muscular strength development may not be necessarily mandatory.

Recent laboratory controlled studies used knee abduction angles and moments as a surrogate measure of ACL injury and examined effects of NMT with and without feedback.^{26, 46, 108, 119, 148} One study measured the effects of verbal and video feedback instruction without NMT in a group of young female volleyball players and reported improvement in landing kinematics after four weeks.¹¹⁹ Additionally, several randomized controlled studies compared landing kinematics between NMT with and without verbal instructions.^{108, 148} The primary findings of the studies were that subjects in both groups (NMT with and without verbal instructions) demonstrated significant improvement in landing kinematics; however, the improvement was greater in NMT with verbal instruction.^{108, 148} To synthesize the available evidence, it is possible to alter lower extremity kinematics by verbal feedback instruction only. However, combining

both NMT, which likely induce muscular strength and verbal feedback, which emphasize desirable movement patterns appear to be most effective intervention.

Effects of compliance on hip abductor, hamstrings, quadriceps and H:Q ratio were analyzed using binary and tertile approaches within the experimental core integrative NMT group. However, results of the both analyses were generally inconsistent and as there were no significant compliance effects. Therefore, the hypothesis for specific aim 2 was not supported. In the binary analysis, there were statistically significant strength increases in left hamstrings in high compliance group compared to low compliance group (Table 7). There was no difference in the remainder of the variables in the binary analysis (Table 7). In the tertile analysis, there were significant differences in left hamstrings, left quadriceps and left H:Q ratio among the three compliance sub-groups (Table 10), and other variables did not demonstrate statistical significant differences. Although there was no prior studies analyzed compliance effects on muscular strength development, two studies analyzed compliance effects on injury risk.^{142, 149} According to the study, there is an inverse dose-response relationship between MNT compliance and ACL injury incidences.¹⁴⁹ Another study reported that female soccer players who participated in preventive NMT with high compliance reduced acute soccer injury incidence by 39% compared to those who participated in moderate compliance level.¹⁴² Based on these reports, the logical assumption was that there is a direct association between NMT compliance and muscular strength development in young female athletes. The binary and tertile compliance effects were exploratory and analyzed based on school levels (Table 11-14). In middle school level, no compliance effects were observed in binary and tertile analyses (Table 11, 13). In high school level, there were significant differences in left hamstrings and left H:Q ratio in binary analysis; however, greater strength development was recorded in the low compliance group (Table 12).

Similar to the binary analysis, significant differences were noted in left hamstrings, left quadriceps, and left H:Q ratio (Table 14). However, the greatest strength gain in left hamstrings and left quadriceps was not from the high compliance group (Table 14). Thus, the compliance effects hypothesized in the specific aim 2 were not found to be tenable even though the school level was stratified.

A potential reason why the compliance effects were not found may be due to the pre-existing strength status. Subjects in high compliance group in both binary and tertile analyses had the greatest pre-intervention strength status for all musculature (Table 6, 9). Thus, the core integrative NMT stimuli were not strong enough to promote musculature strength development in subjects in high compliance group. Specifically, subjects in the high compliance group were older, taller and heavier compared to the low and moderate compliance groups (Table 5, 8); thus, hip abductor, hamstrings, and quadriceps strength were already well developed compared to moderate and low compliance groups. Therefore, subjects in the high compliance group did not respond as well as it was expected although their compliance level was the highest relative the other groups. In contrast, subjects in the moderate and low compliance groups were younger, shorter, and lighter (Table 5, 8) so that the core integrative NMT stimuli were adequate enough to promote greater strength gains since their hip abductor, hamstrings and quadriceps strength were not as well developed as subjects of the high compliance group (Table 6, 9).

In fact, literature suggests that females who have weak hip abductor improve their hip abductor strength at a greater rate compared to individuals with average hip abductor strength.^{20, 25, 35, 69, 97} A systematic review study reported that females who have patellofemoral pain syndrome (PFPS) showed weaker hip abductor, hip external rotator, and hip extensor strength compared to healthy females.¹²⁸ Several studies that incorporated hip strengthening exercises to

physically active individuals with PFPS found approximately 21% to 30% of hip abductor strength increases compared to their pre-testing values.^{25, 35, 69} In contrast, according to a few studies that strengthened hip musculature in a healthy female population, the hip abductor strength gain was relatively smaller and ranged from 10% to 17%.^{20, 97} These studies explain that the lower that pre-existing strength is, the greater potential muscular strength gains. Therefore, the minimum strength gains observed in this study may be due to the pre-existing strength status of the high compliance group of the experimental core integrative NMT group.

Based on the ROC curve analysis, there was no identifiable number of the experimental core integrative NMT sessions that lead to optimum hip abductor peak torque (Table 15; Figure 7-8). Based on the visual inspection, 7.5 and 13.5 sessions of the experimental core integrative NMT were identified as a point to maximize sensitivity and minimize false-positive rate for optimum right and left hip abductor peak torque development (Table 16; Figure 7-8). Although the identified number of the experimental core integrative NMT sessions (7.5) for right hip abductor peak torque is low, the experimental core integrative NMT sessions (13.5) for left hip abductor peak torque appeared to be valid. A total of 20 sessions were needed to develop two standard deviation greater hip abductor peak torque in young female athletes by applying the same core integrative NMT.⁹⁷ The positive likelihood ratio at the 7.5 and 13.5 sessions of the experimental core integrative NMT was 0.84 and 1.13, which can be classified as a minimal likelihood ratio change⁵¹ and did not generate clinically meaningful interpretation. The highest positive likelihood ratio for both right and left hip abductor peak torque was observed at 29.5 session of the experimental core integrative NMT, which was 3.2 and 3.1 for right and left hip abductor peak torque. This can be interpreted that subjects who performed the experimental core integrative NMT greater than 29.5 sessions were approximately three times likely to develop hip

abductor peak torque greater than the cut-off values (41.68 Nm for right and 39.82 Nm for left). The positive likelihood ratio of 3.2 and 3.1 would be considered as small to moderate; however, the sensitivity of detecting the number of NMT for optimum right and left hip abductor was approximately 0.5%, and no statistical significance was noted for both right and left hip abductor peak torque (Table 11).

Although there was no identifiable number of NMT sessions for optimal left H:Q ratio (Table 15-16; Figure 10), there was a statistically identifiable number of NMT sessions for optimum right H:Q ratio development (Table 15-16; Figure 9). Based on the visual inspection of the figure 9, the identifiable number of core integrative NMT session was 14.5. The positive likelihood ratio of 1.2 can be classified as a minimal likelihood ratio change.⁵¹ The greatest positive likelihood ratio (10.2) for developing the optimum right H:Q ratio development was found at the point where subjects completed greater than 28.5 experimental core integrative NMT sessions.

The identified core integrative NMT session of greater than 28.5 for developing the optimum H:Q ratio was high if identified number of the experimental core integrative NMT session is applicable to both right and left H:Q ratio. Only 5.4% of the subjects in the experimental core integrative NMT group complied to greater than 28 NMT sessions. . In addition, 28.5 NMT sessions in one season could be calculated to approximately nine times per a month, which can be equivalent to two NMT sessions per week. Two core integrative NMT sessions per week is the same as in-season protocol of this study. (Three times per week during pre-season and two times per week during in-season) However, during analysis, it was found that some teams did not even have an opportunity to perform two practices per week, especially during in-season. Comparing the results of this study with other literature, a study implemented a

basic resistance training protocol for 30 minutes three times per week for eight weeks and documented that approximately 0.6 of H:Q ratio in the female high school volleyball players.⁷⁶ Also, another study incorporated a 45-60 minutes of plyometric exercises for three times per week for six weeks into a group of young female athletes and reported approximately 0.6 of H:Q ratio.¹⁵² The number of NMT sessions of the both studies ranged from 18 to 24, which was slightly lower than this study. However, the duration of each NMT session appeared to be longer than the current study. Therefore, to synthesize the evidence of the two studies, 28.5 sessions of core integrative NMT can be considered as a valid number to lead to optimum H:Q ratio.

Limitations

There are several limitations in this study. First, the cluster randomization gave almost equal number of teams between the experimental core integrative and control speed/agility NMT groups in basketball and soccer; however, randomization was not ideal in volleyball. Only four teams were allocated to the control speed/agility group compared to 14 teams in the experimental core integrative NMT group (Figure 4). Secondly, a cross contamination between the experimental core integrative and the control speed/agility NMT groups occurred. A specific intervention was assigned in each arm, and intervention providers of each arm gave the assigned intervention correctly; however, several athletes were recruited to more advanced team during the intervention period, which resulted in that the several subjects experienced both interventions. Since the current analysis was performed under an ITT principle, the data were analyzed according to the team they were initially allocated. Third, a few soccer and volleyball teams did not have adequate time to perform assigned intervention during pre-season because of limited duration and divergent timing of pre-season. Specifically, the pre-season duration of the soccer and volleyball teams in middle schools was approximately two weeks. In contrast, pre-

season duration of basketball was about four weeks. Another challenge occurred with soccer and volleyball teams was a start time of the pre-season. The pre-season of soccer and volleyball teams generally started from middle or end of July. Even though a study coordinator tried reaching the coaching staff to schedule pre-testing several weeks before start of the pre-season, in fact, some of the coaches were out of their offices or difficult to reach due to summer break. Therefore, a few teams started their routine trainings and did not schedule their pre-testing sessions either the middle or end of the pre-season. Therefore, the time they could perform the assigned intervention was very limited. Thus, the pre-season intervention compliance was significantly lower in soccer and volleyball. Fourth, it was difficult to check rigor of intervention practicing, record tracking, and compliance reporting from each intervention provider. In order to maintain reliability of providing interventions (both experimental core integrative and control speed/agility groups) among intervention providers, all intervention providers received a mandatory intervention training prior to initiation of the intervention. Additionally, instructions were specifically highlighted in the intervention provider booklets with pictures. A mini laptop was also provided to give specific instructions of each exercise. Furthermore, a study coordinator periodically visited each team to ensure performing each exercise correctly. However, instruction variability within intervention providers may have occurred. For record tracking and compliance tracking, a study coordinator ensured that each intervention provider submitted their records weekly. However, how rigorously each intervention provider tracked attendance, completion and number of exercises performed was unclear. One study analyzed abilities of record tracking including athletic exposures between coaches and athletic trainer.¹⁶³ This study reported that approximately 96.7% of athletic exposures were reported by athletic trainers compared to 36.5% by coaches.¹⁶³ Although the present study did not require athletic exposures information from

coaches, it is uncertain how rigorously each intervention provider managed tracking necessary information.

Conclusion

The current prospective randomized control trial was designed to examine effectiveness of NMT on ACL injury reduction in young female athletes. Because recently published studies reported hip muscular strength improvement following NMT intervention, in particularly NMT that involves proximal segments from knee joints, our study focused on investigating efficacy of the core integrative NMT and effects of the NMT compliance on hip abductor, hamstrings, quadriceps peak torque, and H:Q ratio. Also, it was aimed to determine identifiable NMT session for optimum hip abductor peak torque and H:Q ratio development. It was hypothesized that subjects in the experimental core integrative NMT group would increase hip abductor, hamstrings and quadriceps peak torque and H:Q ratio compared to subjects in the control speed/agility NMT group. However, the hypothesis was not supported in general. Subsequently, compliance effects were analyzed within the experimental core integrative NMT group with categorizing subjects into binary and tertile compliance cohorts based on individual compliance rates. In general, although several variables demonstrated significant muscular increases, the compliance effects on hip abductor, hamstrings and quadriceps peak torque and H:Q ratio were inconsistent. ROC curve analysis did not generate identifiable number of core integrative NMT session for optimal hip abductor peak torque development. However, identifiable number of core integrative NMT sessions was detected in right H:Q ratio. Subjects who performed the core integrative NMT greater than 14.5 sessions likely develop the optimum H:Q ratio.

Several potential reasons for the limited muscular strength gain included a short duration of NMT sessions, few number of repetitions, and a lack of strengthening exercises for lower

extremity musculature. Additionally, pre-existing muscular strength status may explain the reason why compliance effects were not present in this study. Subjects who showed high NMT compliance also demonstrated greater hip musculature; thus, musculature strength gains were minimal. A few other limitations of this study were unequal number of volleyball teams between experimental core integrative NMT and control speed/agility NMT groups, a cross-contamination of several subjects, limited pre-season intervention time for soccer and volleyball teams, and inability to check rigor of record tracking in intervention providers. Future cluster randomized control study using athletic population need to consider those limitations.

Table 5.1. Example of individual compliance calculation.

	Session 1	Session 2	Session 3	Session 4	Session 5	Individual compliance
Athlete A	√	√		√	√	4
Athlete B	√	√	√	√	√	5
Athlete C	√		√		√	3

- Individual compliance = Summation of a NMT session that individuals on roster attended and completed.

Table 5.2. Description of demographic information between experimental and control groups

Variables	Experimental group	Control group	P-values
Number of teams (athletes):	34 teams (276 athletes)	22 teams (163 athletes)	
Basketball	14 team(97 athletes)	13 teams (92 athletes)	
Soccer	6 teams (57 athletes)	5 teams (44 athletes)	
Volleyball	14 teams (122 athletes)	4 teams (27 athletes)	
Physical characteristics:			
Height (cm)	160.9 ± 8.5	160.4 ± 7.9	.525
Weight (kg)	54.1 ± 11.8	55.5 ± 13.1	.267
BMI	20.7 ± 3.5	21.3 ± 4.2	.155
Age (years)	13.9 ± 1.7	13.8 ± 1.7	.486
Age distribution:			
11	51	23	
12	37	33	
13	52	44	
14	62	24	
15	42	17	
16	22	14	
17	8	8	
18	2	0	
Pubertal status:			
Pre-pubertal	22	7	
Pubertal	145	93	

Post-pubertal	109	63	
Previous knee injuries:			
Yes	43	33	
No	233	130	
Previous knee surgeries:			
Yes	1	1	
No	275	162	
Previous prevention program participation:			
Yes	36	13	
No	240	150	
Previous performance enhancement participation:			
Yes	89	39	
No	187	124	
Number of pre-season practices:	12.2 ± 8.4	14.5 ± 9.0	.007*
Basketball	18.4 ± 8.8	19.0 ± 8.1	.597
Soccer	3.5 ± 5.2	7.2 ± 7.7	.008
Volleyball	11.2 ± 4.4	10.5 ± 0.9	.110
Number of in-season practices:	31.8 ± 11.0	29.2 ± 10.6	.018*
Basketball	34.8 ± 8.5	32.0 ± 10.4	.045
Soccer	39.6 ± 13.1	30.1 ± 9.1	.001
Volleyball	25.7 ± 8.2	18.1 ± 5.4	.001
Number of competitions:	22.4 ± 6.4	24.0 ± 4.8	.002*
Basketball	24.6 ± 2.9	25.1 ± 3.3	.211

Soccer	17.6 ± 7.4	22.7 ± 7.1	.001
Volleyball	22.9 ± 6.9	22.4 ± 3.4	.646

*P=0.05

Table 5.3. Mean and standard deviation of hip abductor, hamstrings, quadriceps and H:Q ratio between experimental and control groups in pre-testing

Variables	Experimental group (N=276)	Control group (N=163)	P - values
Hip abductors (N m):			
Right	53.9 ± 13.3	54.7 ± 14.9	0.569
Left	53.0 ± 14.2	54.0 ± 14.7	0.489
Hamstrings (N m):			
Right	41.9 ± 9.8	40.6 ± 10.9	0.220
Left	42.0 ± 10.2	41.3 ± 11.5	0.498
Quadriceps (N m):			
Right	66.4 ± 16.7	69.4 ± 18.4	0.076
Left	64.7 ± 16.5	66.7 ± 17.6	0.257
H:Q ratio:			
Right	0.66 ± 0.17	0.61 ± 0.17	0.005*
Left	0.67 ± 0.17	0.64 ± 0.18	0.068

* P < 0.05

Table 5.4. Mean and standard deviation of strength change of hip abductor, hamstrings, quadriceps and H:Q ratio between experimental and control groups

Variables	Experimental group (N=276)	Control group (N=163)	P - values
Hip abductors (N m):			
Right	1.3 ± 10.6	0.9 ± 10.3	0.829
Left	1.5 ± 10.8	1.1 ± 11.5	0.845
Hamstrings (N m):			
Right	1.5 ± 8.7	1.8 ± 8.2	0.281
Left	1.0 ± 9.0	3.1 ± 10.3	0.158
Quadriceps (N m):			
Right	3.1 ± 7.9	3.6 ± 9.5	0.671
Left	2.2 ± 7.7	3.1 ± 9.9	0.524
H:Q ratio:			
Right	-0.013 ± 0.149	-0.009 ± 0.149	0.112
Left	-0.012 ± 0.171	+0.139 ± 0.166	0.443

* P < 0.05

Table 5.5. Description of demographic information between low and high compliance groups

Variables	Low compliance (N=149)	High compliance (N=127)	P-values
Number of teams (athletes):	149 athletes	127 athletes	
Basketball	40 athletes	57 athletes	
Soccer	16 athletes	42 athletes	
Volleyball	93 athletes	28 athletes	
Physical characteristics:			
Height (cm)	159.2 ± 8.3	162.9 ± 8.4	.001*
Weight (kg)	52.5 ± 12.6	56.0 ± 10.5	.012*
BMI	20.5 ± 3.7	21.0 ± 3.1	.237
Age (years)	13.3 ± 1.5	14.7 ± 1.6	.001*
Pubertal status:			
Pre-pubertal	18	4	
Pubertal	90	55	
Post-pubertal	41	68	
Previous knee injuries:			
Yes	15	28	
No	134	99	
Previous knee surgeries:			
Yes	0	1	
No	149	126	

Previous Prevention program participation:			
Yes	20	16	
No	129	111	
Previous performance enhancement participation:			
Yes	36	53	
No	113	74	
Number of pre-season practices:	9.6 ± 5.2	15.2 ± 10.2	.001*
Basketball	12.1 ± 5.9	22.8 ± 7.8	.001
Soccer	2.7 ± 6.1	3.8 ± 4.9	.509
Volleyball	9.5 ± 3.5	17.0 ± 0.0	.001
Number of in-season practices:	25.1 ± 8.9	39.4 ± 7.8	.001*
Basketball	29.6 ± 7.8	38.5 ± 6.9	.001
Soccer	22.4 ± 12.3	45.3 ± 6.9	.001
Volleyball	23.6 ± 8.1	32.5 ± 2.8	.001
Number of competitions:	22.8 ± 6.3	22.0 ± 6.6	.299
Basketball	24.9 ± 2.4	24.4 ± 3.3	.389
Soccer	10.1 ± 4.7	20.1 ± 6.4	.001
Volleyball	23.8 ± 5.5	19.9 ± 9.7	.053
Number of pre-season exercises:	11.4 ± 19.8	82.5 ± 55.0	.001*
Basketball	30.4 ± 27.2	103.3 ± 69.0	.001
Soccer	10.8 ± 16.5	40.1 ± 5.2	.509

Volleyball	3.5 ± 7.1	104.0 ± 0.0	.001
Number of in-season exercises:	38.6 ± 25.9	109.6 ± 34.5	.001*
Basketball	49.5 ± 14.1	83.9 ± 23.1	.001
Soccer	46.0 ± 32.5	128.8 ± 35.6	.001
Volleyball	32.8 ± 27.0	133.0 ± 0.0	.001
Number of exercises in entire season:	50.0 ± 38.7	192.1 ± 68.6	.001*
Basketball	79.8 ± 37.3	187.2 ± 89.1	.001
Soccer	56.8 ± 46.7	168.9 ± 40.7	.001
Volleyball	36.3 ± 29.9	237.0 ± 0.0	.001

* P < 0.05

Table 5.6. Mean and standard deviation of isokinetic strength values of hip abductor, hamstrings, quadriceps and H:Q ratio between low and high compliance groups in pre-testing

Variables	Low compliance group (N=149)	High compliance group (N=127)	P - values
Hip abductors (N m):			
Right	52.7 ± 13.9	55.4 ± 12.4	0.108
Left	51.6 ± 14.3	54.6 ± 13.9	0.081
Hamstrings (N m):			
Right	41.4 ± 9.7	42.5 ± 10.0	0.377
Left	41.8 ± 10.6	42.2 ± 9.8	0.735
Quadriceps (N m):			
Right	63.3 ± 16.5	70.0 ± 16.2	0.001*
Left	62.2 ± 15.8	67.8 ± 16.9	0.004*
H:Q ratio:			
Right	0.68 ± 0.17	0.63 ± 0.17	0.009*
Left	0.70 ± 0.19	0.64 ± 0.15	0.007*

* P < 0.05

Table 5.7. Mean and standard deviation of strength change of hip abductor, hamstrings, quadriceps and H:Q ratio between low and high compliance groups

Variables	Low compliance group (N=149)	High compliance group (N=127)	P – values
Hip abductors (N m):			
Right	0.80 ± 9.72	1.96 ± 11.67	0.693
Left	1.28 ± 9.60	1.68 ± 12.11	0.447
Hamstrings (N m):			
Right	2.16 ± 9.22	0.72 ± 8.06	0.735
Left	0.69 ± 8.30	1.26 ± 9.81	0.003*
Quadriceps (N m):			
Right	3.05 ± 7.67	3.09 ± 8.21	0.733
Left	2.58 ± 7.62	1.70 ± 7.89	0.527
H:Q ratio:			
Right	-0.0085 ± 0.150	-0.01890 ± 0.148	0.783
Left	-0.0219 ± 0.169	+0.0003 ± 0.173	0.112

* P < 0.05

Table 5.8. Description of demographic information among low, moderate and high compliance groups

Variables	Low compliance	Moderate compliance	High compliance	P-values
Number of teams (athletes):	101 athletes	93 athletes	82 athletes	
Basketball	9 athletes	58 athletes	30 athletes	
Soccer	12 athletes	12 athletes	34 athletes	
Volleyball [#]	80 athletes	23 athletes	18 athletes	
Physical characteristics:				
Height (cm)	159.2 ± 8.0	159.9 ± 8.7	164.2 ± 8.1	.001*
Weight (kg)	52.0 ± 12.5	53.6 ± 11.7	57.3 ± 10.5	.009*
BMI	20.3 ± 3.7	20.8 ± 3.4	21.2 ± 3.2	.250
Age (years)	13.1 ± 1.3	13.7 ± 1.6	15.2 ± 1.4	.001*
Pubertal status:				
Pre-pubertal	13	7	2	
Pubertal	69	44	32	
Post-pubertal	19	42	48	
Previous knee injuries:				
Yes	8	14	21	
No	93	79	61	
Previous knee surgeries:				
Yes	0	0	1	
No	101	93	81	

Previous prevention program participation:				
Yes	11	14	11	
No	90	79	71	
Previous performance enhancement participation:				
Yes	23	29	37	
No	78	64	45	
Number of pre-season practices:	8.9 ± 5.1	15.1 ± 7.5	12.9 ± 10.9	.001*
Basketball	14.2 ± 7.8	16.7 ± 8.1	22.8 ± 8.8	.002
Soccer	0.2 ± 0.6	11.6 ± 7.6	2.0 ± 0.0	.001
Volleyball	9.5 ± 3.6	12.9 ± 4.4	17.0 ± 0.0	.001
Number of in-season practices:	21.9 ± 7.5	33.5 ± 7.1	41.8 ± 7.6	.001*
Basketball	27.4 ± 8.7	32.5 ± 7.2	41.5 ± 6.5	.001
Soccer	19.1 ± 10.3	35.1 ± 11.3	47.7 ± 1.3	.001
Volleyball	21.6 ± 6.7	35.4 ± 3.6	31.1 ± 2.5	.001
Number of competitions:	22.1 ± 7.1	21.9 ± 6.1	23.3 ± 5.9	.310
Basketball	24.3 ± 2.7	24.5 ± 2.5	24.7 ± 4.0	.920
Soccer	8.2 ± 0.6	18.6 ± 5.8	20.3 ± 6.6	.001
Volleyball	23.7 ± 5.6	17.0 ± 8.9	26.5 ± 4.5	.041
Number of pre-season exercises:	6.7 ± 20.5	42.3 ± 39.7	92.4 ± 57.1	.001*
Basketball	41.2 ± 55.6	42.2 ± 38.9	142.7 ± 58.7	.001
Soccer	5.7 ± 13.7	31.8 ± 8.1	42.0 ± 0.0	.001

Volleyball	2.9 ± 6.7	47.1 ± 49.6	104.0 ± 0.0	.001
Number of in-season exercises:	30.6 ± 25.1	68.3 ± 31.5	124.7 ± 21.7	.001*
Basketball	50.1 ± 19.1	57.0 ± 16.8	100.2 ± 14.2	.001
Soccer	41.0 ± 26.8	70.6 ± 48.4	142.1 ± 9.5	.001
Volleyball	26.9 ± 24.2	94.5 ± 34.9	133.0 ± 0.0	.001
Number of exercises in entire season:	37.3 ± 38.8	110.6 ± 64.4	217.2 ± 49.6	.001*
Basketball	91.3 ± 72.1	99.2 ± 53.3	242.8 ± 67.6	.001
Soccer	46.7 ± 39.1	102.5 ± 56.4	184.1 ± 9.0	.001
Volleyball	29.8 ± 27.6	141.6 ± 82.5	237.0 ± 0.0	.001

* P < 0.05

Table 5.9. Mean and standard deviation of isokinetic strength values of hip abductor, hamstrings and H:Q ratio among low, moderate and high compliance groups in pre-testing

Variables	Low compliance (N=101)	Moderate compliance (N=93)	High compliance (N=82)	P - values
Hip abductors (N m):				
Right	52.6 ± 14.1	52.7 ± 13.0	57.1 ± 12.3	0.045*
Left	51.4 ± 15.2	51.2 ± 13.2	57.0 ± 13.2	0.010*
Hamstrings (N m):				
Right	42.2 ± 9.5	39.4 ± 9.7	44.2 ± 9.9	0.005*
Left	42.8 ± 10.5	39.8 ± 9.7	43.5 ± 9.9	0.041*
Quadriceps (N m):				
Right	61.7 ± 16.1	67.0 ± 15.8	71.5 ± 17.0	0.001*
Left	60.7 ± 15.7	64.9 ± 15.6	69.7 ± 17.2	0.001*
H:Q ratio:				
Right	0.71 ± 0.17	0.61 ± 0.16	0.64 ± 0.17	0.001*
Left	0.73 ± 0.20	0.63 ± 0.14	0.65 ± 0.16	0.001*

P < 0.05

Table 5.10. Mean and standard deviation of isokinetic strength change values of hip abductor, hamstrings and H:Q ratio among low, moderate and high compliance groups

Variables	Low compliance (N=101)	Moderate compliance (N=93)	High compliance (N=82)	P – values
Hip abductors (N m):				
Right	0.64 ± 9.38	1.29 ± 10.70	2.27 ± 12.09	0.821
Left	1.98 ± 10.34	1.51 ± 11.07	0.76 ± 11.19	0.190
Hamstrings (N m):				
Right	1.96 ± 9.68	2.23 ± 7.86	0.10 ± 8.42	0.548
Left	-0.76 ± 8.18	3.62 ± 9.76	0.06 ± 8.74	0.001*
Quadriceps (N m):				
Right	3.69 ± 7.49	2.29 ± 8.13	3.11 ± 8.12	0.184
Left	3.40 ± 7.21	0.95 ± 8.19	2.26 ± 7.46	0.009*
H:Q ratio:				
Right	-0.0193 ± 0.163	0.0112 ± 0.130	-0.0302 ± 0.151	0.837
Left	-0.0600 ± 0.169	0.0565 ± 0.161	-0.0276 ± 0.162	0.001*

* P < 0.05. In left hamstrings, Bonferroni correction test indicated p=0.001 between low and moderate compliance. Bonferroni correction test also indicated p=0.005 between low and high compliance. In left quadriceps, Bonferroni correction test indicated 0.051 between low and high compliance. In left H:Q ratio, Bonferroni correction test found p=0.001 between low and moderate compliance groups.

Table 5.11. Mean and standard deviation of strength change of hip abductor, hamstrings, quadriceps and H:Q ratio between low and high compliance groups in middle school

Variables	Low compliance group (N=107)	High compliance group (N=27)	P – values
Hip abductors (N m):			
Right	0.19 ± 9.45	-1.84 ± 12.35	0.883
Left	0.28 ± 9.78	0.38 ± 11.48	0.349
Hamstrings (N m):			
Right	1.82 ± 9.54	3.51 ± 7.96	0.735
Left	0.27 ± 8.27	3.48 ± 7.73	0.511
Quadriceps (N m):			
Right	3.59 ± 7.08	4.93 ± 7.86	0.792
Left	2.65 ± 6.69	4.64 ± 4.40	0.591
H:Q ratio:			
Right	-0.0193 ± 0.161	-0.0079 ± 0.167	0.988
Left	-0.0343 ± 0.178	-0.0040 ± 0.168	0.921

Table 5.12. Mean and standard deviation of strength change of hip abductor, hamstrings, quadriceps and H:Q ratio between low and high compliance groups in high school

Variables	Low compliance group (N=39)	High compliance group (N=99)	P – values
Hip abductors (N m):			
Right	2.43 ± 10.36	2.93 ± 11.35	0.379
Left	3.96 ± 8.64	2.01 ± 12.30	0.473
Hamstrings (N m):			
Right	3.09 ± 8.32	-0.04 ± 7.96	0.956
Left	1.85 ± 8.36	0.65 ± 10.26	0.001*
Quadriceps (N m):			
Right	1.59 ± 9.06	2.58 ± 8.27	0.913
Left	2.41 ± 9.83	0.90 ± 8.44	0.605
H:Q ratio:			
Right	-0.0211 ± 0.113	-0.0220 ± 0.143	0.644
Left	+0.0120 ± 0.140	+0.0015 ± 0.175	0.023*

* P < 0.05

Table 5.13. Mean and standard deviation of strength change of hip abductor, hamstrings, quadriceps and H:Q ratio between low and high compliance groups in middle school

Variables	Low compliance (N=77)	Moderate compliance (N=48)	High compliance (N=5)	P – values
Hip abductors (N m):				
Right	0.65 ± 9.09	-0.40 ± 10.34	-11.39 ± 16.09	0.051
Left	0.81 ± 10.40	0.11 ± 9.41	-5.69 ± 11.56	0.125
Hamstrings (N m):				
Right	1.57 ± 10.20	3.03 ± 7.70	5.15 ± 9.99	0.329
Left	-0.99 ± 8.50	3.56 ± 6.95	5.80 ± 10.89	0.590
Quadriceps (N m):				
Right	3.88 ± 7.02	3.27 ± 7.03	8.52 ± 9.37	0.177
Left	3.00 ± 6.50	2.89 ± 6.29	5.56 ± 6.55	0.816
H:Q ratio:				
Right	-0.0291 ± 0.174	0.0118 ± 0.128	-0.0422 ± 0.279	0.387
Left	-0.0665 ± 0.187	0.0337 ± 0.117	-0.0138 ± 0.331	0.495

Table 5.14. Mean and standard deviation of strength change of hip abductor, hamstrings, quadriceps and H:Q ratio between low and high compliance groups in high school

Variables	Low compliance (N=23)	Moderate compliance (N=40)	High compliance (N=74)	P – values
Hip abductors (N m):				
Right	0.59 ± 10.53	3.32 ± 10.90	3.19 ± 11.34	0.286
Left	5.90 ± 9.34	3.19 ± 12.70	1.19 ± 11.11	0.715
Hamstrings (N m):				
Right	3.23 ± 7.74	1.26 ± 8.03	-0.24 ± 8.27	0.455
Left	0.03 ± 7.11	3.70 ± 12.42	-0.33 ± 8.53	0.009*
Quadriceps (N m):				
Right	3.05 ± 9.04	1.11 ± 9.23	2.75 ± 7.97	0.689
Left	4.75 ± 9.26	-1.37 ± 9.58	2.04 ± 7.51	0.014*
H:Q ratio:				
Right	0.0133 ± 0.114	0.0104 ± 0.135	-0.0294 ± 0.142	0.806
Left	-0.0385 ± 0.084	0.0838 ± 0.200	-0.0286 ± 0.148	0.001*

* P < 0.05

Table 5.15. Area under curve, standard error, 95% confidence interval and asymptotic significance of hip abductor and H:Q ratio with individual compliance rate

Variables	Area under curve	95% CIs		Asymptotic significance
		Lower bound	Upper bound	
Hip abductors (N m):				
Right	.437 ± .050	.340	.535	0.211
Left	.473 ± .051	.373	.574	0.597
H:Q ratio:				
Right	.600 ± .035	.533	.668	0.005*
Left	.561 ± .036	.490	.633	0.089

* P < 0.05

Table 5.16. Cut-off score, core integrative NMT session number, true positive rate, false positive rate, and positive likelihood ratio of hip abductor and H:Q ratio

Variables	Cut-off score	Core integrative NMT session	True positive rate	False positive rate	Positive likelihood ratio
Hip abductors (N m):					
Right	41.68	7.5	.622	.740	0.840
Left	39.82	13.5	.605	.534	1.133
H:Q ratio:					
Right	0.6	14.5	.589	.411	1.434
Left	0.6	7.5	.804	.678	0.117

Figure 5.1. Example of performing isokinetic hip abductor strength test.

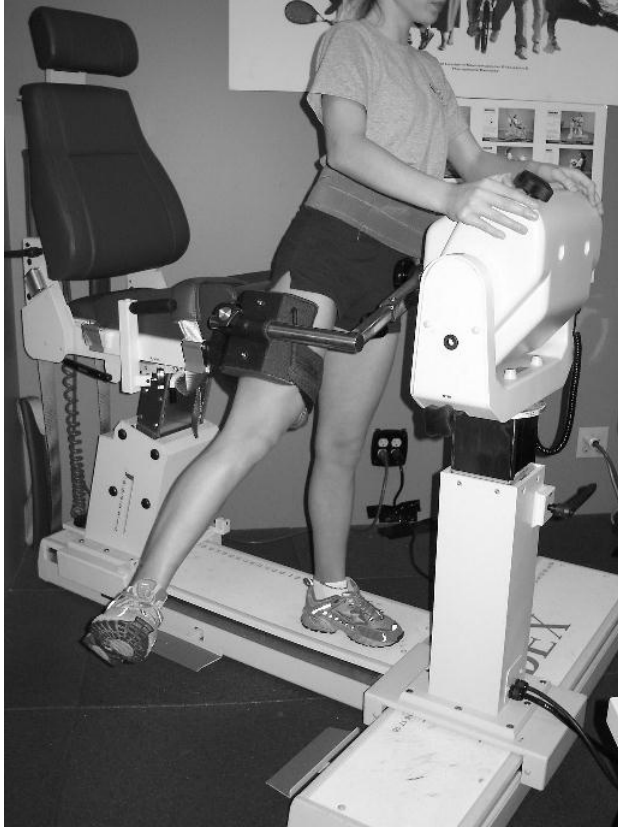


Figure 5.2. Example of performing isokinetic hamstrings and quadriceps strength test.



Figure 5.3. Example of performing resistive forward running with a tubing band.



Figure 5.4. Flow chart of team allocation between experimental and control groups

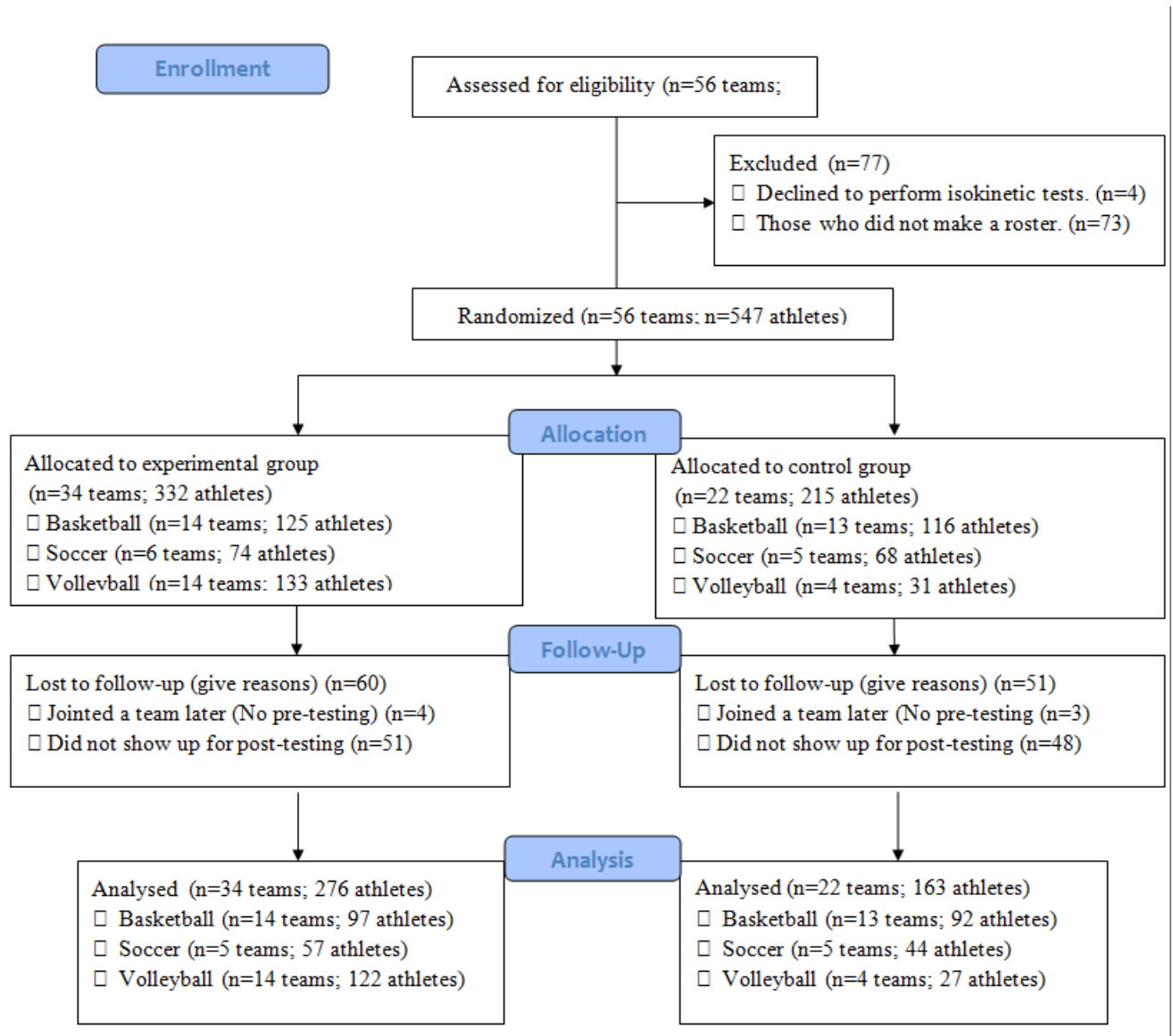


Figure 5.5. Flow chart of binary compliance groups

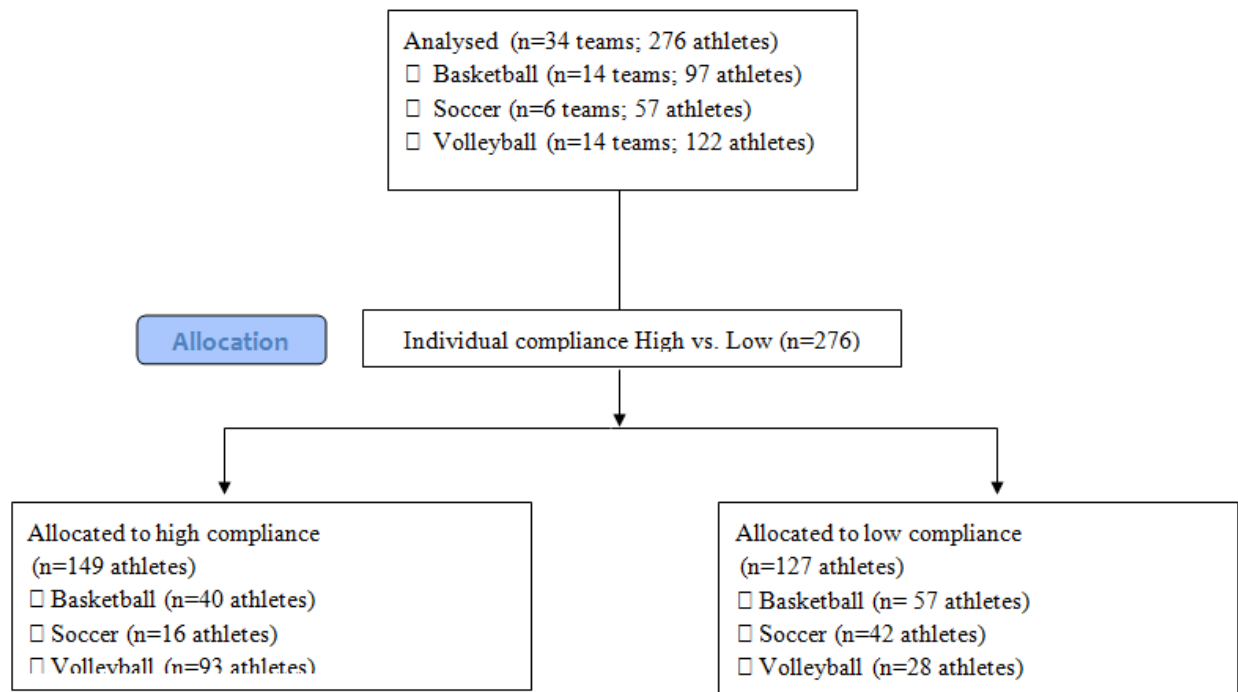


Figure 5.6. Flow chart of tertile comparison groups

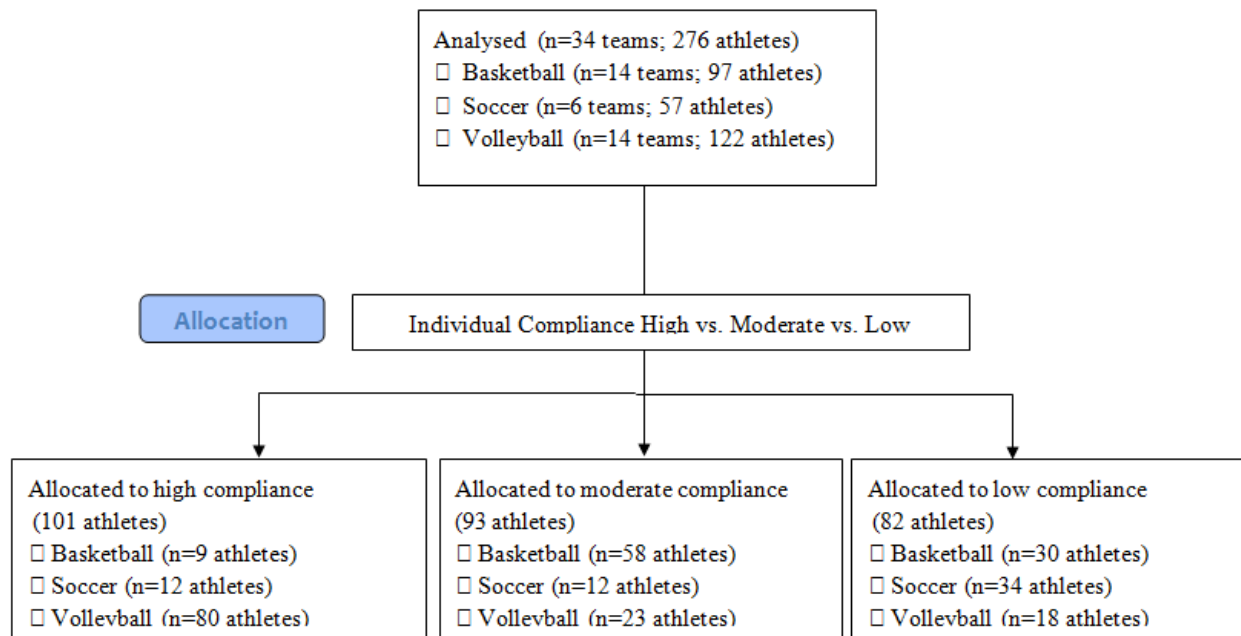
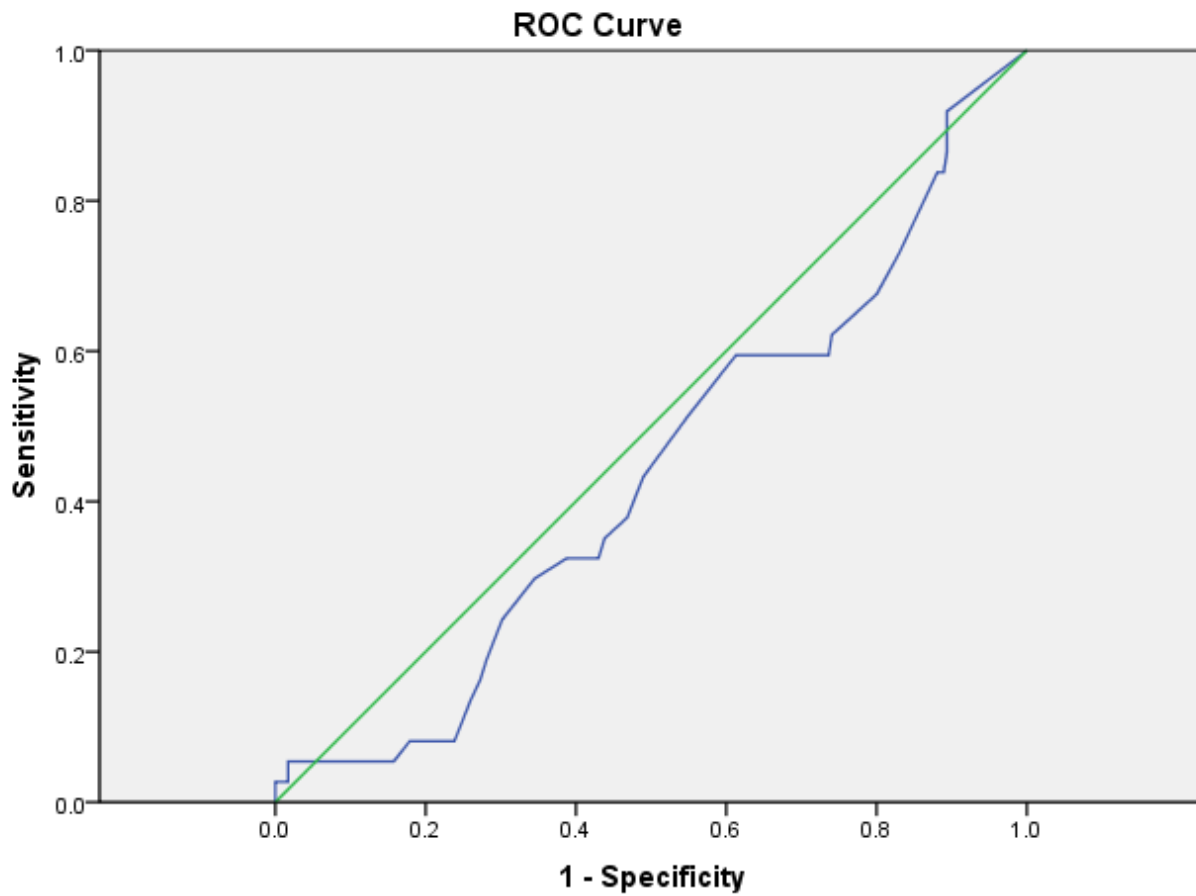
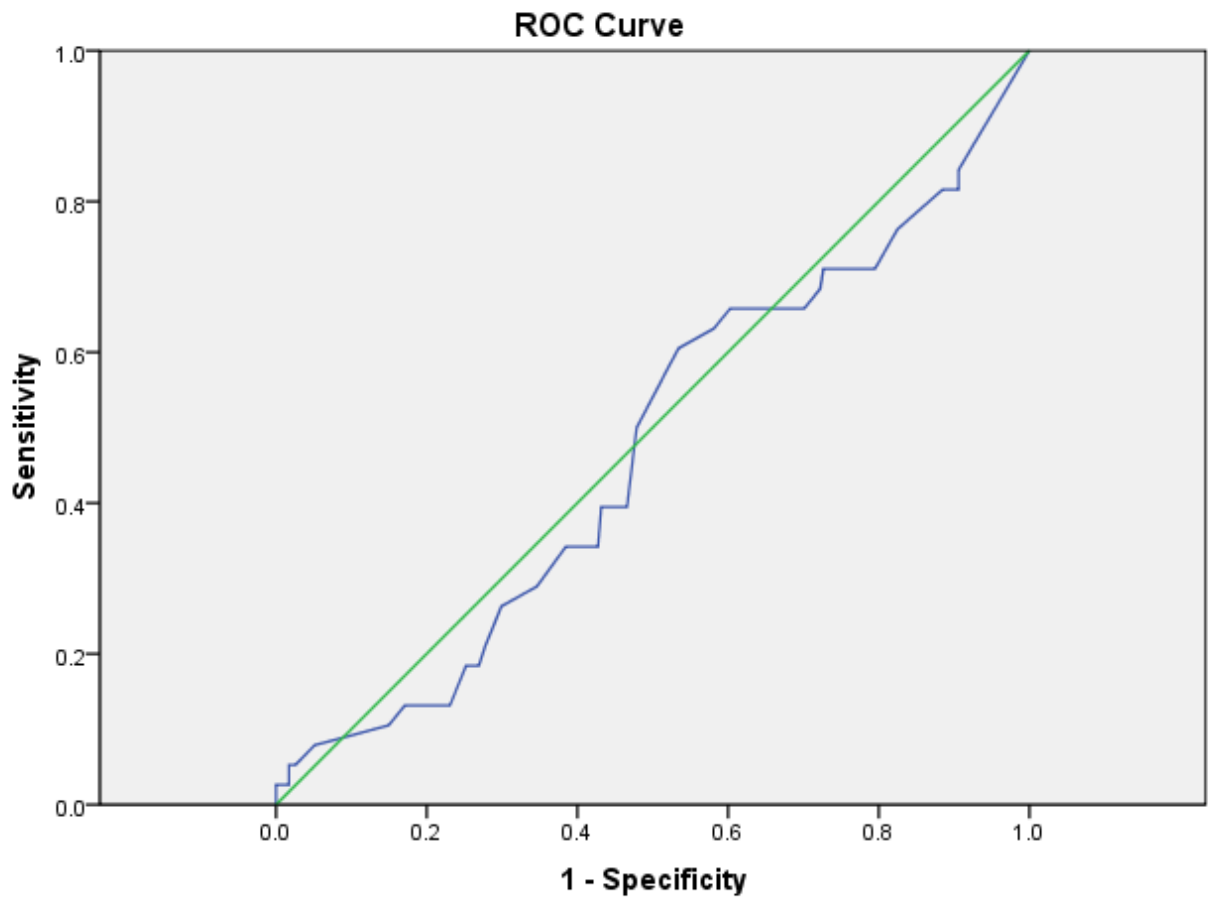


Figure 5.7. ROC curve for right hip abductor peak torque



Diagonal segments are produced by ties.

Figure 5.8. ROC curve for left hip abductor peak torque



Diagonal segments are produced by ties.

Figure 5.9. ROC curve for right H:Q ratio

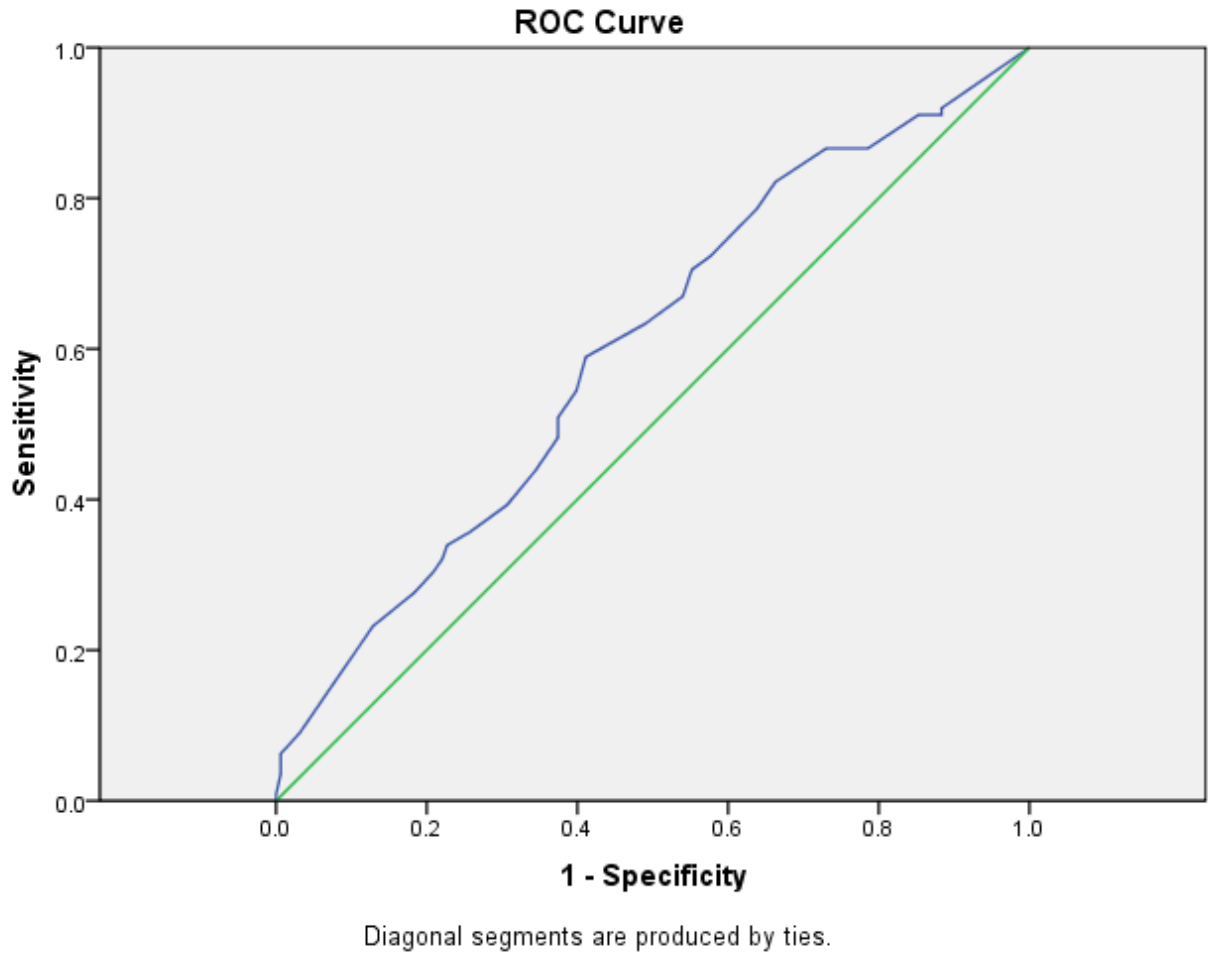
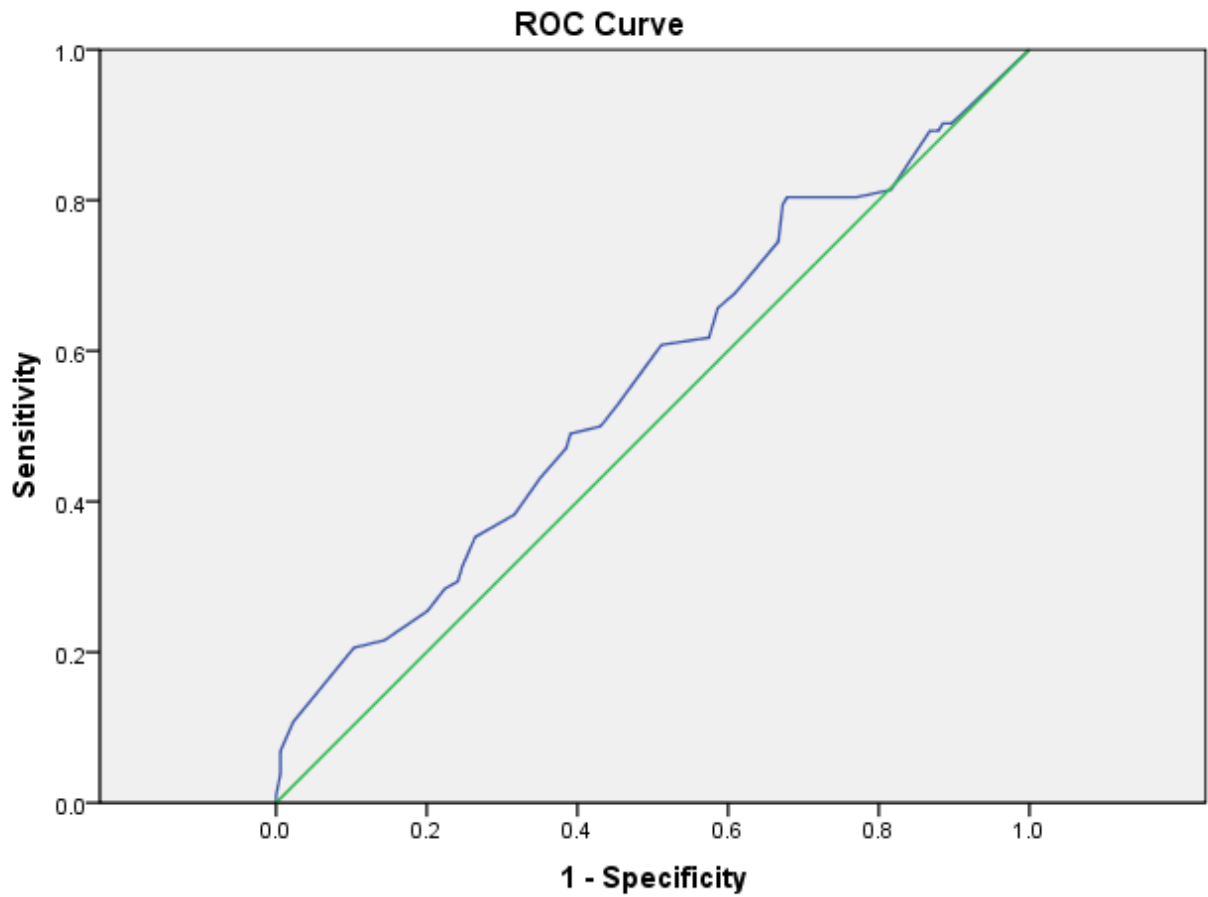


Figure 5.10. ROC curve for left H:Q ratio



Diagonal segments are produced by ties.

Chapter 6 Summary

Purposes, Aims and Hypotheses

The following purposes, specific aims and hypotheses were examined throughout the different chapters of this dissertation:

1. *Purpose:* To describe common pathomechanics of ACL injury and also identify distribution of the common ACL pathomechanics based on sexes.
2. *Purpose:* To provide an up to date analyses aimed to determine the effectiveness of neuromuscular training interventions designed to reduce both noncontact and overall ACL injury risk in female athletes through relative risk reduction and numbers-needed-to-treat analyses.
3. *Purpose:* To investigate whether or not compliance of neuromuscular training plays a role in reducing ACL injury incidents in young female athlete.

Hypothesis: Neuromuscular training studies with high compliance rates would result in lower ACL incidence rates in young female athletes.
4. *Purpose:* To investigate compliance effect of proximal neuromuscular training, a trunk and hip focused integrative neuromuscular training, on isokinetic hip abductor strength in young female athletes.

Hypothesis: Female athletes who demonstrated the higher compliance to a trunk and hip focused isokinetic hip abductor strength would show a greater hip abductor strength enhancement.

5. *Purpose:* To determine the effect of a trunk and hip focused integrative neuromuscular training compliance on hip abductor, hamstrings and quadriceps peak torque and H:Q ratio in young female athletes.

Aim 1: To determine the effect of neuromuscular training on hip abductor, hamstrings, quadriceps peak torque and H:Q ratio between an intervention (experimental core integrative neuromuscular training) and control (control speed/agility neuromuscular training) groups of young female athletes.

Hypothesis 1: Subjects in the experimental core integrative neuromuscular training demonstrate greater hip abductor, hamstrings, quadriceps peak torque and H:Q ratio when compared to subjects in a control speed/agility neuromuscular training group.

Aim 2: To compare the effect of neuromuscular training compliance on hip abductor, hamstrings and quadriceps peak torque and H:Q ratio in young female athletes.

Hypothesis 2: Greater hip abductor, hamstrings and quadriceps peak torque and H:Q ratio changes are observed in groups with higher neuromuscular training compliance rates compared to lower neuromuscular training compliance group within an intervention group.

Aim 3: To determine the number of neuromuscular training sessions to lead to optimal hip abductor peak torque and H:Q ratio in the experimental core integrative NMT group.

Hypothesis 3: There is an identifiable number of neuromuscular training sessions that demonstrate optimal hip abductor peak torque and H:Q ratio.

Summary of Findings

The following are summaries of the findings for each of the purposes and specific aims:

1. *Purpose:* To describe common pathomechanics of ACL injury and also identify distribution of the common ACL pathomechanics based on sexes.

Finding: Three common pathomechanics of ACL injury are noncontact, indirect contact, and direct contact mechanisms. Among the three pathomechanisms, majority of the ACL injury occurs with noncontact mechanisms. In male athletes, approximately 55% of the ACL injury consists of noncontact mechanism, and approximately 70% of ACL injury consists of noncontact mechanism in female athletes.

2. *Purpose:* To provide an up to date analyses aimed to determine the effectiveness of neuromuscular training interventions designed to reduce both noncontact and overall ACL injury risk in female athletes through relative risk reduction and numbers-needed-to-treat analyses.

Finding: Relative risk reduction of ACL injury in female athletes using neuromuscular training generated 73.4% and 43.8% for noncontact and overall ACL injury. The numbers-needed-to-treat analysis estimated that 108 and 120 athletes need to perform a neuromuscular training program to prevent one noncontact and overall ACL injury.

3. *Purpose:* To investigate whether or not compliance of neuromuscular training plays a role in reducing ACL injury incidents in young female athlete.

Finding: Female athletes who performed neuromuscular training with high compliance rates demonstrated lower ACL injury incidence rates compared to female athletes who practiced neuromuscular training with low compliance rates.

4. *Purpose:* To investigate compliance effect of proximal neuromuscular training, a trunk and hip focused integrative neuromuscular training, on isokinetic hip abductor strength

in young female athletes.

Finding: Female athletes who demonstrated the higher compliance to a trunk and hip focused isokinetic hip abductor strength showed significantly greater isokinetic hip abductor strength compared to female athletes who were in control group.

5. *Purpose:* To determine the effect of a trunk and hip focused integrative neuromuscular training compliance on hip abductor, hamstrings and quadriceps peak torque and H:Q ratio in young female athletes.

Aim 1: To determine effect of neuromuscular training on hip abductor, hamstrings, quadriceps peak torque and H:Q ratio between an intervention (experimental core integrative neuromuscular training) and control (control speed/agility neuromuscular training) groups of young female athletes.

Finding: There were no differences in hip abductor, hamstrings, quadriceps and H:Q ratio between the experimental core integrative neuromuscular training and control speed/agility neuromuscular training group of young female athletes.

Aim 2: To compare the effect of neuromuscular training compliance on hip abductor, hamstrings and quadriceps peak torque and H:Q ratio in young female athletes.

Finding: There were no neuromuscular training compliance effects on hip abductor, hamstrings and quadriceps peak torque and H:Q ratio within young female athletes in the experimental core integrative neuromuscular training.

Aim 3: To determine the number of neuromuscular training sessions to lead to optimal hip abductor peak torque and H:Q ratio in the experimental core integrative NMT group.

Findings: There was no identifiable number of neuromuscular training that lead to the

optimal hip abductor peak torque and H:Q ratio within young female athletes in the experimental core integrative neuromuscular training.

Synthesis of Results

From these study findings, a few conclusions and implications for future research were suggested:

1. Among three ACL pathomechanics (noncontact, indirect contact, and direct contact), majority of ACL injury consists of noncontact mechanism. The noncontact ACL injury was more common mechanism in female athletes (approximately 70%) compared to male athletes (approximately 55%). In short, female athletes often tear their ACL as a result of their own movements and did not involve contact with another athlete or object.
2. Relative risk reduction of the noncontact ACL injury in female athletes by applying neuromuscular training was 73.4%. Also, relative risk reduction of overall ACL injury (any type of ACL injuries including indirect contact and direct contact mechanism) was 43.8% of overall ACL injury. Therefore, neuromuscular training can be used as an effective intervention to modify risk factors associated with ACL injury in young female athletes.
3. Although the neuromuscular training is an effective intervention to reduce ACL injury in young female athletes, compliance to the neuromuscular training needs to be high. Compared female athletes who participated in given neuromuscular training more than 2/3, female athletes who participated in given neuromuscular training less than 1/3 demonstrated approximately five times greater ACL injury incidence rates, and the

ACL injury incidence rates were the same as those who did not perform neuromuscular training. Hence, compliance is an imperative aspect of ACL injury prevention.

4. The compliance effects on muscular strength development in young female athletes were conflicting. One study (chapter four) documented compliance effects on hip abductors strength with performing a core integrative neuromuscular training. However, another study (chapter five) did not record compliance effects on hip abductors, hamstrings, and quadriceps peak torque and H:Q ratio. One potential explanation was pre-existing strength status. Subjects who were classified in a high compliance group demonstrated greater lower extremity muscular strength in pre-intervention test, which may account for the reason why their lower extremity strength development did not differ from subjects who were classified in a moderate and low compliance sub-groups.
5. Compliance is ability to follow a given instruction. For neuromuscular training intervention research studies (chapter four and five), there were two different levels of compliance: 1) compliance of intervention providers to a study protocol and 2) compliance of subjects to a given neuromuscular training. In this project (chapter five), 2) compliance of subjects to a given neuromuscular training was used as a compliance measure and expressed as individual compliance. The number of individual compliance to the experimental core integrative NMT ranged from 0 to 32 in this project (chapter five). The individual compliance rate was vastly influenced by 1) compliance of intervention providers to a study protocol because if the intervention providers did not follow a study protocol, subjects cannot comply to the given neuromuscular training, which as a result, reduce an individual compliance rate.

Therefore, 1) compliance of intervention providers to a study protocol affects 2) compliance of subjects to a given neuromuscular training.

6. The study protocol of the current study (chapter five) was to perform a given neuromuscular training 15 to 30 minutes three times per week during pre-season and 10-15 minutes two times per week during in-season. However, in reality, a few intervention providers who were mostly coaches of their own teams did not follow the study protocol because of consecutive game schedules, unexpected weather condition, and impromptu practice cancellations, especially during in-season at middle school levels. Those factors hindered 1) compliance of intervention providers to a study protocol, which further reduces 2) compliance of subjects to a given neuromuscular training.

Conclusions and Future Research Implications

This dissertation focused on investigating an effective intervention that would reduce ACL injury incidence in young female athletes. In order to find the intervention, the most common mechanism of ACL injury in female population needs to be identified. Because noncontact ACL injury is the most common mechanism, neuromuscular training intervention was chosen as a variable of interest since it can potentially modify risk factors of ACL injury in young female athletes. From previously published studies, it was identified that young female athletes who participated in neuromuscular training demonstrated lower ACL injury incidence rates compared to those who did not.¹⁰⁹ Additionally, high compliance to neuromuscular training enhanced prophylactic effectiveness of neuromuscular training, which resulted in further ACL injury reduction in female athletes. However, compliance effects on lower extremity muscular strength were not consistent based on two studies (Chapter four and five) that incorporated in

this dissertation. A potential reason may stem from different pre-existing lower extremity muscular strength status.

This dissertation ensured neuromuscular training is an effective intervention to reduce ACL injury in young female athletic population. However, numbers-needed-to-treat analysis suggested that 108 and 120 female athletes would need to be trained to prevent one noncontact or one overall ACL injury during a course of one competitive athletic season. Although neuromuscular training indicated prophylactic efficaciousness and benefits, the current neuromuscular training may not be practical and implementable for athletic settings because of the fairly large number of athletes need to be trained. Thus, a screening system to identify at-risk athletes need to be developed. Recently, a few screening techniques to identify ACL at-risk female athletes have been introduced^{105, 118} ; however, utility of those screening techniques are unknown. Thus, further investigations are necessary to confirm utility of the screening tool. Additionally, a recent report summarized that lack of knowledge, understanding, and support among coaches, athletes, and athletes' parents were barriers for implementing neuromuscular training in female high school soccer settings.⁶⁸ Therefore, healthcare practitioners need to educate coaches, athletes, and athletes' parents in order to intervene neuromuscular training to reduce ACL injury incidence. Indeed, another study reported a dramatic ACL reduction in female handball athletes after educating coaches through educational website and DVD.¹¹² Hence, healthcare practitioners who engage with physically active population need to engage with educating coaches to enhance their knowledge and understanding of neuromuscular training. Also, neuromuscular training program needs to be tailored to be sport-specific in order to make it practicable in athletic settings, which may further assist successful implementation.

Those future implications could lead to promotion of safe and long-lasting physically active life style in female population.

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VITA

Dai Sugimoto, MS, ATC, CSCS

I. Education

- 2009 - Present University of Kentucky, Lexington, KY
Doctor of Philosophy, Rehabilitation Science - Athletic Training
- 2006 - 2007 Lakeland College, Sheboygan, WI
2000 - 2001 Masters of Education
- 2001 - 2003 University of Rhode Island, Kingston, RI
Masters of Science, Exercise Science
- 1996 - 2000 University of Wisconsin-La Crosse, La Crosse, WI
Bachelor of Science, Exercise and Sports Science - Athletic Training

II. Professional Experiences

- July 2009 - Present Research Assistant
Cincinnati Children's Hospital Sports Medicine
Cincinnati, OH
- July 2005 - June 2009 Head Athletic Trainer
Lakeland College
Sheboygan, WI
- August 2003 - June 2005 Head Athletic Trainer
Seton Hill University
Greensburg, PA
- May 2003 - August 2003 Therapeutic Exercise Instructor
Eleanor Slater Mental Health Hospital
Cranston, RI
- August 2001 - May 2003 Graduate Assistant Athletic Trainer
University of Rhode Island Athletic Department
Kingston, RI
- August 2000 - July 2001 Interim Head and Graduate Assistant Athletic Trainer
Lakeland College Athletic Department
Sheboygan, WI
- July 2000 - August 2000 Athletic Training Student and Safety Coordinator
National Youth Sports Program
La Crosse, WI
- July 1999 - August 1999 Intern Athletic Training Student
New Orleans Saints
La Crosse, WI
- December 1998 - June 1999 Intern Athletic Training Student
Gundersen Lutheran Sports Medicine Center
Onalaska, WI

July 1998 - August 1998 Athletic Training Student and Safety Coordinator
National Youth Sports Program
La Crosse, WI

III. Administrative Activity and University Service

July 2007 - June 2009 Search committee for a faculty hire for Department of Exercise Science and Sport Studies Program, Natural Science Division, Lakeland College, Sheboygan, WI
July 2005 - June 2009 Drug Testing committee Chair for Lakeland Athletics, Lakeland College, Sheboygan, WI
July 2005 - June 2009 Search committee for a coaching staff hire for Lakeland Athletics, Lakeland College, Sheboygan, WI
May 2004 - July 2004 Search committee for a school nurse position, Seton Hill University, Greensburg, PA
Aug 2003 - June 2005 Anti-drug/Alcohol Education and Health Wellness Promotion committee, Seton Hill University, Greensburg, PA

IV. Teaching Activity

University of Kentucky

2013 Spring Basic Athletic Training – Instructor
2013 Spring Orthopaedic Evaluation and Rehabilitation of the Lower Extremity – Guest instructor (one class)
2012 Fall Basic Athletic Training – Instructor
2012 Spring Basic Athletic Training – Guest instructor (two classes)
2011 Summer Musculoskeletal Anatomical Dissection – Teaching assistant
2011 Spring Orthopaedic Evaluation and Rehabilitation of the Lower Extremity – Teaching assistant

Transylvania University

2013 Spring Athletic Injury and Rehabilitation – Guest instructor (five classes)
2012 Spring Anatomy and Physiology II – Instructor for two laboratory sessions
2011 Spring Athletic Injury and Rehabilitation – Guest instructor (five classes)

Lakeland College

2009 Spring Care and Prevention of Athletic Injuries
2008 Fall Care and Prevention of Athletic Injuries – Mentored one student
2008 Fall First Aid and Emergency Care
2008 Spring Kinesiology and Biomechanics
2008 Spring Care and Prevention of Athletic Injuries
2007 Fall Introduction to Fitness Programing – Mentored one student
2007 Fall Physiology of Exercise

2007 Spring	Kinesiology and Biomechanics
2006 Fall	Internship in Fitness – Mentored one student’ internship
2006 Fall	Principle of Physical Fitness
2006 Spring	Physiology of Exercise
2006 Spring	Prevention and Assessment of Athletic Injuries
2005 Fall	Kinesiology and Biomechanics
2005 Fall	Principle of Training
University of Wisconsin-Sheboygan	
2007 Fall	Prevention and Treatment of Athletic Injuries – Guest instructor (five classes)
Others	
July 2010	Kentucky Middle and High School Coaches’ State Conference, Northern Kentucky University, Highland Heights, KY. Lecture on <i>-How to Prevent Heat Related Illness</i>
June 2008	Local Cable TV Station Program “It’s About How You Live Today!” Sheboygan, WI. Guest on <i>-Healthy Walking Everyday</i>
January 2006	Masters of Counseling program, Lakeland College, Sheboygan, WI Guest lecture on <i>-Research Methods and Application in Sports Medicine</i>
December 2005	Plymouth Ambulance Station, Plymouth, WI. Guest lecture on <i>-Emergency Helmet Removal in Athletic Population</i>
November 2005	Physician’s Assistant program, Seton Hill University, Greensburg, PA Guest lecture on <i>-Shoulder orthopaedic examination, treatment and rehabilitation</i>
Jan 2004 - May 2005	Residence Hall program, Seton Hill University, Greensburg, PA Guest lecture on <i>-Balance in your diet and exercises</i>

V. Advising Activity

Nov 2010 - May 2013 Two Masters’ students in Division of Athletic Training, College of Health Science, University of Kentucky

VI. Honors

July 2013	Systematic Review award – The winner from American Journal of Sports Medicine
June 2013	Clint Thompson award for Clinical Advancement – 2 nd runner-up from Journal of Athletic Training
April 2013	Wright Scholarship award from College of Health Sciences, University of Kentucky
April 2012	Diversity Enhancement Scholarship award from College of Health Sciences, University of Kentucky
April 2011	Diversity Enhancement Scholarship award from College

May 2007	of Health Sciences, University of Kentucky
May 2000	Who's Who among America's Teachers and Educators
April 2000	Who's Who among students in American Universities and Colleges
June 1999	UW-La Crosse Scholar-Athlete award from UW-L Athletics, University of Wisconsin – La Crosse
1997-2000	NFL Minority scholarship from Professional Football Athletic Trainers' Society (PFATS) to work with New Orleans Saints summer training camp.
1996-1997	Scholarship from Office of International Education, University of Wisconsin – La Crosse
	Scholastic Achievement award from Office of Residence Life, University of Wisconsin – La Crosse

VII. Speaking Engagements/Presentations

11. June 2013 Poster Presentation: *Dosage Effects of Neuromuscular Training Intervention to Reduce ACL Injuries in Female Athletes*. **Sugimoto D**, Myer GD, Barber Foss KD, Hewett TE, National Athletic Trainers' 64th Annual Meeting and Clinical Symposium, Las Vegas, NV
10. April 2013 Poster Presentation: *Comparison of Isokinetic Hip Abductor and Adductor Peak Torque and Ratio between Sexes*. **Sugimoto D**, Mattacola CG, Mullineaux DR, Palmer TG, Hewett TH. College of Health Science Rehabilitation Science Doctoral Program Colloquium, Lexington, KY.
9. March 2013 Oral Presentation: *Dosage Effects of Neuromuscular Training Intervention to Reduce ACL Injuries in Female Athletes*. **Sugimoto D**, Myer GD, Barber Foss KD, Hewett TE, Southeastern Athletic Trainers' 37th Clinical Symposium and Members Meeting, Atlanta, GA.
8. June 2012 Oral Presentation: *The Influence of Age on the Effectiveness of Neuromuscular Training to Reduce Anterior Cruciate Ligament Injury in Female Athletes*. Myer GD, **Sugimoto D**, Thomas SM, Hewett TE. National Athletic Trainers' 63rd Annual Meeting and Clinical Symposium, St. Louis, MO.
7. June 2012 Oral Presentation: *Effects of Compliance on Trunk and Hip Integrative Neuromuscular Training on Hip Abductor Strength Development in Female Athletes*. **Sugimoto D**, Myer GD, Hewett TE. National Athletic Trainers' 63rd Annual Meeting and Clinical Symposium, St. Louis, MO.

6. March 2012 Oral Presentation: *Effects of Compliance on Trunk and Hip Integrative Neuromuscular Training on Hip Abductor Strength Development in Female Athletes*. **Sugimoto D**, Myer GD, Hewett TE. Southeastern Athletic Trainers' 37th Clinical Symposium and Members Meeting, Atlanta, GA.
5. January 2012 Poster Presentation: *Comparison of Isokinetic Hip Abductor and Adductor Peak Torque and Ratio between Sexes*. **Sugimoto D**, Mattacola CG, Mullineaux DR, Palmer TG, Hewett TH. National Strength & Conditioning Specialists – Kentucky Chapter, Georgetown, KY.
4. June 2011 Special Topic Presentation: *Can We Prevent Noncontact ACL Injury in Female Athletes?* **Sugimoto D**, Myer GD, Hewett TE. National Athletic Trainers' 62nd Annual Meeting and Clinical Symposium, New Orleans, LA.
3. June 2011 Oral Presentation: *Effects of Compliance on Neuromuscular Training to Prevent ACL Injury in Female Athletes*. **Sugimoto D**, Myer GD, Bush HM, Klugman MF, McKeon JM, Hewett TE. National Athletic Trainers' 62nd Annual Meeting and Clinical Symposium, New Orleans, LA.
2. August 2010 Poster Presentation: Kinematics to estimate three-dimensional joint kinematics during walking. Mullineaux DR, Hanaki-Martin S, Jeon K, Cunningham TJ, Shapiro R, Noehren BW, **Sugimoto D**. The 6th World Congress on Biomechanics, Singapore.
1. February 2008 Oral Presentation: *Strategies for Preventing Noncontact ACL Injury in Female Athletes*. **Sugimoto D**. NSCA-Wisconsin Chapter Annual Meeting, University of Wisconsin-Oshkosh, Oshkosh, WI.

VIII. Research Publications

8. **Sugimoto D**, Myer GD, Barber Foss KD, Hewett TE. Dosage effects of neuromuscular training intervention to reduce anterior cruciate ligament injuries in female athletes: Meta- and sub-group analyses. *Sports Med*. Under review.
7. Myer GD, Wordeman SC, **Sugimoto D**, Bates NA, Roewer BD, McKeon JM, Dicesare CA, Di Stasi SL, Barber Foss KD, Thomas SM, Hewett TE. Reliability of injury risk prediction algorithm across three different institutions: Implications for multi-center biomechanical and epidemiological research. *J Appl Biomech*. Accepted

with revision.

6. **Sugimoto D**, Mattacola CG, Mullineaux DR, Palmer TG, Hewett TE. Comparison of isokinetic hip abduction and adduction peak torque and ratio between sexes. *Clin J Sports Med*. Accepted with revision.
5. **Sugimoto D**, Myer GD, Hewett TE. Effects of compliance on trunk and hip integrative neuromuscular training on hip abductor strength development in female athletes. *J Strength Cond Res*. Accepted with revision.
4. Myer GD, **Sugimoto D**, Thomas SM, Hewett TE. The Influence of age on the effectiveness of neuromuscular training to reduce anterior cruciate ligament injury in female athletes. *Am J Sports Med*. 2013; 41(1):203-215
3. **Sugimoto D**, Myer GD, Bush HM, Klugman MF, McKeon JM, Hewett TE. Effect of compliance with neuromuscular training on ACL injury risk reduction in female athletes: a meta-analysis. *J Athl Train*. 2012; 47(6):714-723.
2. **Sugimoto D**, Myer GD, McKeon JM, Hewett TE. Evaluation of neuromuscular training effectiveness to reduce ACL injury in female athletes: A critical review of relative risk reduction (RRR) and Numbers-Needed-to-Treat (NNT) analysis. *Br J Sports Med*. 2012; 46(14): 979-988.
1. **Sugimoto D**, Blanpied PR. Flexible foil exercise and shoulder internal and external rotation strength” *J Athl Train*. 2006; 41:280-285.