This is to certify that the
thesis entitled

THE EFFECTS OF A PLYOMETRIC TRAINING PROGRAM
ON THE NEUROMUSCULAR CHARACTERISTICS OF
FEMALE ATHLETES

presented by

Angela Ann DiPasquale

has been accepted towards fulfillment
of the requirements for the

M.S. degree in Kinesiology

Major Professor's Signature

07/17/2003

Date

THE EFFECTS OF A PLYOMETRIC TRAINING PROGRAM ON THE NEUROMUSCULAR CHARACTERISTICS OF FEMALE ATHLETES

By

Angela Ann DiPasquale

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Kinesiology

2003

ABSTRACT

THE EFFECTS OF A PLYOMETRIC TRAINING PROGRAM ON THE NEUROMUSCULAR CHARACTERISTICS OF FEMALE ATHLETES

By

Angela Ann DiPasquale

Research on the recent popularity and increase in participants in female athletics has shown that there are a greater number of anterior cruciate ligament (ACL) tears that females sustain in comparison to the number of ACL tears suffered by males. Prevention programs are now being implemented in high school and college athletics to attempt to reduce the occurrence of ACL injuries.

Twenty-five college-age female participants (height= 66.02, weight= 132.92, age= 20.32) volunteered as participants. Eleven females were selected to the plyometric training program, while fourteen were used as control subjects. The training program consisted of a variety of plyometric exercises, that were performed for 45 to 60 minutes, 3 days a week, on alternating days, for 6 weeks under the supervision of the investigator. Four testing sessions were held: one prior to the start of the study, and one after weeks two, four and six of the training program. The testing sessions measured the subject's postural control, and hamstring and quadriceps strength.

A repeated measure ANOVA revealed significant interactions for average power and peak torque during concentric flexion at the speed of 120°/sec. However, no statistical significance was found for the postural control or other strength variables. The increased hamstring strength shows that plyometric training may be a good prevention program for young females to utilize to aide in the reduction in the number of ACL tears sustained by female athletes.

ACKNOWLEDGMENTS

I would like to thank my thesis committee members, Dr. Kavin Tsang, Dr. John Powell, and Dr. Chris Womack, for the time that they put forth, and the guidance that they gave through out this process. I would also like to thank the participants of my research project. I couldn't have done it without their time and dedication. Many thanks to my family and friends who have always believed in me and supported me through out the years.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1

INTRODUCTION

As the popularity of female sports continues to rise, an elevation in the intensity of competition between female athletes has occurred. This increase in the level of play amongst female athletes places more pressure on the athletes to become quicker, stronger, and faster to remain competitive in their respective sport. Recently research efforts have focused on female athletes and their higher injury rates when compared with those of male athletes. One area of particular concern is the greater rate of anterior cruciate ligament (ACL) injuries that females sustain in comparison to the number of ACL injuries suffered by males.

Previous studies have shown that female athletes have a higher incidence of injury in sport.[1, 2] High school female basketball players were shown to have more injuries, more time lost due to injury, require surgery more frequently[3], and have a higher rate of knee injuries.[4] Particularly compelling is the number of ACL tears sustained by female athletes.[4-6] The average number of ACL injuries per intercollegiate basketball program was reported to be 2.37 for females and .71 for males over a four year period, with incidence rates per 100 players of 3.52 for females, and .98 for males.[7] Arendt and Dick[5] reported that the ACL injury rate per 1000 athlete exposures for female soccer players was .31, which was double that of the male players (.13). Also, the female basketball players had an injury rate (.29), four times the male injury rate (.07).

The most alarming statistic with female ACL injuries is that a majority of the injuries are caused by noncontact mechanisms, such as landing from a jump and cutting.[5] During contact injuries the cause of the injury is known, but with noncontact injuries the reason for injury in unknown. Various research studies have been conducted to try to determine the causes of these noncontact injuries and to identify specific risk factors for ACL injury.of the injury in unknown.

Two intrinsic factors thought to risk factors for ACL ruptures are hamstring and quadriceps strength, and postural control.[8] The ratio of hamstring strength to quadriceps strength is important in an athlete because the hamstrings act as a knee stabilizer. The hamstrings help to resist anterior tibial translation at the knee, which is also the function of the ACL, so the less the hamstrings are able to reduce the amount of anterior tibial translation, the more strain and load that is placed on the ACL.

Females were observed by Soderman et al.[9] to have a lower hamstring to quadriceps ratio during concentric action, and that this factor was related to a higher risk of traumatic injury. Specifically, of the five players in the study that sustained ACL tears, all of them had hamstring to quadriceps ratios lower than 55% on the ACL injured side than on their noninjured side.[9] Female athletes were also found to have a significant decrease in hamstring to quadriceps ratio bilaterally when compared to male athletes.[10] Male athletes tend to be hamstring dominant, make a higher hamstring to quadriceps ratio, while females tend to be quadriceps dominant, resulting in a lower ratio.[11]

Postural control is controlled by joint stability and proprioceptive mechanisms. During movements in sport postural control is constantly being altered, and the ACL plays an important role in supporting postural control. Ankle stability is important at the knee because the ankle influences tibial orientation and effects the positioning of the ACL.[12] Increased postural sway values, which indicate poor balance, corresponded with higher ankle sprain rates. The athletes with poor balance sustained seven times as many ankle sprains as those with decreased postural sway values, which indicate better balance.[13] While a paucity of research has been conducted on the effects of postural sway values on incidence of knee injuries, it has been shown that the enhancement of proprioception and muscular strength are equally effective in promoting joint stability and balance maintenance.[12]

An injury to an athlete's ACL has a great impact on the person physically, emotionally and financially. There is a great amount of time lost from the sport, time spent during rehabilitation, and a financial burden due to surgery and other costs.[14-16] There are numerous theories as to why this trend is occurring in females. Several studies[14-17] have looked at the various intrinsic and extrinsic factors that are different between the genders that may be causing this increased rate of injury. Only recently has the research[18-21] started to focus on how training programs can prevent the occurrence of ACL injuries through various techniques to improve strength, impact forces, proprioception, and identification of potential ACL injuring situations.

A variety of methods have been used in the recent prevention training programs. One study[20] used a video titled "ACL Awareness Program" to help decrease the number of severe knee sprains suffered amongst experienced skiers.[20] Other studies looked at the effects of proprioception training programs on the number of ACL injuries in male and female soccer players[19, 21]. A study by Hewett et al.[18] observed the effect of a jump-training program on the incidence of knee injury in female athletes. The program had already been shown to decrease impact forces at the knee and increase hamstring strength.[22] After participating in the plyometric jump training program, trained particpants had a reduced incidence of knee injury when compared with the untrained, which the investigators attributed to an increased dynamic stability of the knee joint.

Plyometric training consists of exercises that help improve muscles' strength and power. The basic principle of plyometrics is to preload the muscle with an eccentric contraction, and follow that with a quick concentric contraction. The eccentric preloading of the muscle induces the myostatic stretch reflex of the muscle and caused a more forceful concentric contraction.[23] Hewett et al.[22] reported that plyometric training can safely improve lower body strength and power in female athletes. Plyometric exercises have also been shown to promote joint stabilizatioin and the use of efficient, functional motor patterns.[24] Trochnanteric bone mineral content, leg strength and balance in adolescent females all improved after a nine month plyometric training program.[25]

The purpose of this study was to evaluate the effects of a plyometric jump training program on the neuromuscular characteristics of female athletes. It was hypothesized that the plyometric training program will improve the subjects' postural control and strength of the hamstring and quadriceps muscles. Any improvements seen in these measures may help reduce the number of knee injuries in these athletes. This could lead to the development and use of programs like this one by female athletes at the high school and college levels.

Chapter 2

LITERATURE REVIEW

Ever since Title IX was instituted in 1972, there has been an increase in the amount of females playing sports. The purpose of this act was to ensure equal rights to male and female athletes at federally funded institutions.[26] Within twenty years of its enactment, the number of female college athletes rose from 10,000 to 100,000.[16] With the increase in the number of participants, female sports began to be played at a faster, more precise and powerful skill level. Though female athletes are beginning to play at earlier ages and have better coaching and improved skills, their injury rate of anterior cruciate ligament (ACL) tears has not decreased.

Arendt et al.[27] studied ACL injury patterns among collegiate men and women participating in basketball and soccer. Their study reviewed data that was submitted to the NCAA Injury Surveillance System from 1989-1999. In the latter five years they found that the rate, based on the number of injuries per 1000 athlete exposures, of total ACL injuries in women soccer players was .33, as compared to .12 in males. Female basketball players had a rate of .29, while the male players had a rate of .10. These rates are significantly different between the genders, and led the authors to conclude that female athletes involved in basketball and soccer suffer ACL injuries at significantly higher rates than college-age men in the same sports. Their results also suggest that neither lack of skill, nor lack of years of playing experience are the primary causative factor for injury.

Messina, Farney and DeLee[4] compared the injury rates between male and female high school basketball players over the course of one season. The results showed that the females had a significantly higher rate of lower extremity injuries and knee injuries, their rate was 2.3 times greater than the rate of the male athletes. The incidence of knee injuries in the female athletes was .71 per 1000 player-hours, as compared with the .31 for the males. The female population was also found to have a significantly higher incidence of ACL injury (.025%), which was 3.6 times higher than the male athletes (.007).

ANATOMY

The knee joint is comprised of the tibia, femur, patella, anterior cruciate ligament, posterior cruciate ligament, lateral collateral ligament, medial collateral ligament, the menisci, and numerous muscle tendons. Three different joints form the knee complex: tibiofemoral, patellofemoral, and superior tibiofibular. The tibiofibular joint is comprised of the articulations between the condyles of the femur and tibia, the patellofemoral joint lies between the patella and femoral condyles and the superior tibiofibular joint is the articulation between the head of the fibula and tibia.

The femur is the longest and strongest bone in the body. At the distal end are the lateral and medial condyles, which are covered with hyaline cartilage so they can articulate with the tibia. The tibia is the major weight-bearing bone of the leg. The tibial plateau is located at the top of the proximal end of the tibia and articulates with the femur. The patella is located in front of the tibiofemoral joint in the patellar tendon. It covers and protects the anterior portion of the knee.

The medial and lateral collateral ligaments support and stabilize the knee by reinforcing the tibiofemoral joint capsule and preventing abnormal movement of the knee from side to side. They provide restraint against valgus and varus stresses to the knee, respectively. The menisci are pads of fibrocartilage attached to the plateau of the tibia. They help provide shock absorption, assist in control of normal knee motion and enhance the total stability of the knee. The posterior cruciate ligament (PCL) is the shortest and strongest of the cruciate ligaments. It arises from the posterior aspect of the tibia and then passes medially to the anterior cruciate ligament and attaches to the lateral portion of the femur's medial condyle. The function of the PCL is to help restrain against posterior displacement of the tibia on the femur.

The anterior cruciate ligament is approximately 3.5 cm long and 1.1 cm wide.[28] It arises from the anteromedial intercondylar tubercle of the tibia and travels posteriorly and laterally to attach to the medial wall of the lateral femoral condyle. It has two discrete segments, an anteromedial bundle and a posterolateral bundle. The anteromedial band runs from the proximal femoral attachment to the anteromedial aspect of the tibial attachment, while the posterolateral band inserts on the posterolateral tibial attachment. In flexion, the anteromedial band is taught, and as the knee moves into extension, this band becomes slack and the posterolateral band becomes tighter.[29] The ACL serves as a stabilizer against anterior translation of the tibia on the femur, internal rotation of the tibia on the femur, external rotation of the tibia on the femur, and hyperextension of the tibia. It also works as a secondary restraint against valgus and varus stresses.

Many muscles contribute to the movement, stability, and support of the knee joint. The main extensor muscle is the quadriceps, which is comprised of the vastus medialis, vastus lateralis, vastus intermedius and rectus femoris. Each has a common attachment to the tibial tuberosity via the patellar tendon. The hamstring muscle group, sartorius, gracilis, gastrocnemius and popliteus are all knee flexors. The hamstring muscle group is made up of the semitendinosus, semimembranosus and biceps femoris. The gracilis, sartorius and semitendinosus all form a common tendon called the pes anserine muscle group, which attaches to the medial aspect of the tibia and assists in medial stability of the knee.

In relation to the ACL, the hamstrings act as a protagonist by reducing anterior tibial translation and internal tibial rotation during flexion.[30] They function with the ACL to help provide anterior knee stability. The quadriceps also stabilize the knee joint by contracting eccentrically. A deficit in eccentric hamstring strength relative to eccentric quadriceps strength could predispose an athlete to an ACL injury.[31] This is especially important in female athletes who tend to be more quadriceps dominant.[11]

ETIOLOGY

The ACL can be injured a number of different ways. It can sustain an injury from either a direct contact or a noncontact mechanism. Alarmingly, the majority of female ACL injuries occur from noncontact mechanisms.[32] Arendt et al.[27] reported that 63% of women soccer players' ACL injuries were from no apparent contact, as compared with 48% of the males' injuries. In the women's basketball data, no apparent contact accounted for 80% of the injuries. Noyes et al. [33] found that 4/5 of ACL injuries occurred from noncontact injuries, with the majority occurring when landing from a jump.

Three main noncontact mechanisms have been found: planting and cutting, straight-knee landing, and one-step stop landing with the knee hyperextended.[32] These mechanisms put the knee into hyperextension or externally rotate the tibia with the knee in a valgus position and therefore place an excessive rate of strain on the ACL.

Noncontact injuries typically occur during deceleration of the body.[16] The "position-of-no-return" has also been described as a noncontact mechanism. This position is described as the back in forward flexion, the hip in adduction and internal rotation, 20-30^{o} of knee flexion, external rotation of the tibia and forefoot pronation.[34]

RISK FACTORS

There are multiple factors that contribute to the females' increased rate of noncontact ACL injuries. These factors are classified as intrinsic, extrinsic and both.[26] Intrinsic factors are uncontrollable by the athlete and are related to the knee's anatomy, while extrinsic factors originate outside of the knee joint, and are potentially controllable by the athlete.[35] A risk factor that is categorized as both extrinsic and intrinsic in nature, is partially controllable by the athlete. Skill and coordination are factors that are classified as both intrinsic and extrinsic.[26] Extrinsic factors include body movement, muscular strength, conditioning, type of shoes, motivation, coaching differences, skill level, the use of braces and deceleration forces during injury. Joint laxity, size of the ACL, lower extremity malalignments, genu recurvatum, dimensions of the intercondylar notch, and hormones are intrinsic factors that predispose female athletes to injury.[34]

Extrinsic Risk Factors

In a survey taken in 1994 by the Chronicle of Higher Education, coaches of women's teams were only paid 59 cents on the dollar as compared with men's coaches.[36] While compensation of coaches does not correlate with their quality, experience or expertise, the ability to recruit the best coaches is often affected by the payment offered. Also, funding for Division I female sports is about 40% compared with male sports. This lack of financial support may lead to inferior equipment and athletic shoes, unsafe playing fields, and less individualized coaching.[36] These factors may contribute to the greater number of ACL injuries in female athletes by having them participating is sports with less experienced coaches, and in unsafe conditions and environments.

Muscular strength is important in maintaining knee stability. Studies have shown that women have a deficit in hamstring strength relative to quadriceps strength when compared to male athletes.[10] It has been hypothesized that a hamstring to quadriceps ratio lower than 60% in males and females can predispose an athlete to ACL injury.[37] Since the hamstrings act to help control anterior tibial translation, any diminished strength of the hamstrings could predispose an athlete to an ACL injury, by increasing the amount of strain and load placed on the ACL.

Females also have different muscle activation patterns than males. Huston and Wojtys[11] observed that female athletes tend to activate their quadriceps first in response to anterior tibial translation, while the male and control subjects in the study recruited their hamstrings first. Shultz et al.[38] did not find the same results in muscle recruitment patterns between male and female athletes. The male and female subjects in their study demonstrated similar muscle-recruitment patterns in response to a perturbation, but the females activated their quadriceps earlier than the male subjects. The added anterior force caused by the quadriceps can stress the ACL further by pulling anteriorly on the tibia via the patellar tendon at small angles of knee flexion.[39] The added strain from the quadriceps, in combination with weak hamstrings, places the ACL under great strain.

Male and female athletes have been observed to have different jumping and landing characteristics. Females tend to have a more erect posture, with an extended knee and hip, which increases the amount of forces felt by the body during landing.[40] If landing forces are applied over a short period of time, without accommodating joint movement, there is less opportunity for the body to absorb the forces. Full range of motion of a joint allows enough time for the forces to be absorbed by the body.[41] Gray-McNitt[42] found that the peak vertical ground reaction forces could be decreased if the knee is in the maximum degree of flexion.

Intrinsic Risk Factors

Anatomic alignment differences have also been indicated as possible causes of ACL injury. The Q-angle is the angle formed by the intersection of a line from the anterior superior iliac spine to the center of the patella and a line from the center of the patella to the tibial tubercle. A larger than normal Q-angle is often associated with tibial internal rotation[43] and the ACL functions to prevent internal rotation. If internal tibial rotation is increased in females by their Q-angles then this may compromise the integrity of the ACL. The large Q-angles of females also place medial stress on the knee because of the pull of the rectus femoris on the patella. Q-angles have been found to be greater in female athletes when compared with Q-angles of male athletes.[10]

Other anatomical considerations can create positions that are common to ACL injury mechanisms. Females have wider pelvic bones, increased femoral anteversion, increased genu valgum, increased genu recurvatum, increased external tibial torsion and more forefoot pronation.[44] These malalignments increase the energy consumption and mechanical stresses of the body.[29] Faulty alignments place the joint into a position that has preloaded stress onto the ligaments and therefore, cause structural failure under external forces well below the critical stress limits.[29, 45, 46]

Hormonal influences are another internal factor possible for putting females at greater risk for ACL ruptures. Female athletes are exposed to rhythmic variations in endogenous hormones during their menstrual cycles or via oral contraceptives. More and more research is being done on how a female's menstrual cycle and its fluctuating hormones may affect the laxity of the ACL, therefore predisposing females for injury at certain times in their cycle. There are three phases of the menstrual cycle: menstrual (days 1-5), follicular (days 6-14) and luteal (days 15-28).[47] These phases are a series of cyclic changes that the uterine endometrium undergoes, month after month, as it responds to changing levels of ovarian hormones, estrogen and progesterone, in the blood.

Only a few studies have been performed to study the correlation between the menstrual cycle and its hormonal changes, and ACL injuries and laxity. Heitz et al.[47] observed significant differences in ACL laxity in conjuction with estrogen and progesterone surges during their menstrual cycles. The greatest amount of ACL laxity was found during the luteal phase, where progesterone levels increase. From the results, it was concluded that female ACL laxity significantly increases in conjunction with surging levels of estrogen and progesterone during the normal menstrual cycle.

Another study, done by Wojtys et al.[48], investigated the variation in ACL injury rates during the menstrual cycle. The results of their study found a significant association between the stage of the menstrual cycle and the likelihood for an ACL injury. There were more injuries during the ovulatory (follicular) phase than was expected. This increased rate of ACL injury in females during this phase suggests that the frequent occurrence of ACL tears may be related to hormonal fluctuations. The study concluded that the association found between the noncontact ACL injury rates in female athletes and the reported phase of their menstrual cycle is a cause for concern.

If the hormones do not directly affect the ACL, they may have some effect on the elements that predispose females to ACL tears. The role that the hormones play on the risk factors of ACL injuries is a topic that has yet to be extensively studied. The intrinsic factors, such as muscle strength, joint laxity and proprioception, may become more apparent during certain phases of the menstrual cycle or at specific levels of the sex hormones circulating through the body, making female athletes more susceptible to injury at certain times. If a correlation could be found between the level of hormones circulating throughout the body and another intrinsic factor, more prevention measures could take place so that many of the ACL tears could be avoided.

ACL INJURY PREVENTION STRATEGIES

At Vermont ski resorts, Ettlinger et al.[20] observed an increasing rate of severe knee sprains, while the overall rate for lower extremity injury decreased. They attributed the decline to the introduction of the releasable ski binding, but then noted that there are no products that have been implemented to sense and respond to potential injury causing loads on the knee. This led them to design an experimental program for advanced skiers with the purpose of developing an awareness of events leading to severe knee sprains in these skiers. They hoped that the "ACL Awareness Training" would reduce the number of severe knee sprains to the ACL among experienced skiing professionals.

The training program was divided into three sections. The first part dealt with avoiding high-risk behavior. The subjects watched a video of skiers falling, and at various points were asked to record answers to questions in the workbooks provided.

The questions asked about the positioning of the skiers limbs and skis up to the point of injury. The video was followed by a discussion session, where the leader and participants developed profiles for the mechanism of injury, and then devised strategies as to how to respond quickly and effectively to the risk of ACL injury. To conclude the session, all the participants contributed to the development of guidelines for avoiding high-risk behavior. Section two assisted the subjects in recognizing potentially dangerous situations by presenting them with a list of the six elements of the phantom-foot injury mechanism. Part three recommended specific strategies for responding to these potentially high risk situations.

The "ACL Awareness Training" program was implemented among the on-slope ski staff at 20 ski areas. Data was also recorded at 22 ski areas, where the program was not utilized, to be used as control data. The analyzing of the data showed that there was a decrease of 62% in ACL injuries among the ski staff that had completed the training program, while no reduction in the number of injuries occurred in the control group. The investigators concluded that an effort should be made to teach skiers how and when to fall, and how to stop after falling. They suggest that an education program would be a cost-effective means for helping to reduce the risk of ACL injuries among experienced professional alpine skiers.

Caraffa et al.[19] examined the use of proprioception as an intervention to decrease the rate of ACL injury. Twenty male semi-professional and amateur soccer teams received proprioception training, while twenty did not. The teams involved with the training were instructed to train for at least 20 minutes every day during the preseason, and three days a week during their active season. The proprioceptive training was divided into five phases of increasing difficulty and was utilized over the course of three seasons. The injury data recorded indicated that the trained teams had ten ACL injuries over the three seasons and an injury rate of .15 injuries per team per season, while the untrained group had 70 injuries and an injury rate of 1.15 injuries per team per season. From this data, the authors were able to conclude that proprioceptive training can reduce the number of ACL injuries in soccer. The authors also suggested that proprioceptive training should become a standard practice in the preseason and in season conditioning of teams.

Soderman et al.[21] conducted a research study on the effects of balance board training on female soccer players. Seven teams from the second and third Swedish divisions served as the experimental group, while six teams were used as controls. The experimental participants were given a balance board and a training program, so they could complete the exercises at home. Participants were told to perform the exercises each day for the first 30 days, and then 3 days a week during the rest of the soccer season (about 6 months). The program took about 10 to 15 minutes to complete.

In contradiction to Caraffa et al.[19], the investigators of this article found no effect of the balance board training on the number, incidence, or type of traumatic injuries of the lower extremity. When comparing the experimental and control groups, the balance training group showed a significantly higher incidence rate of major injuries than the controls. Knee sprains were the most common major injury in the intervention group, and 4 out of the 5 ACL injuries occurred in this group as well. Therefore, the authors concluded that balance board training did not prevent ACL injuries in female soccer players.

Hewett et al.[18] studied the effect of a jump-training program on the incidence of knee injuries in female athletes. The program was designed to increase joint stability by increasing the strength of the muscles surrounding the joint, and to decrease the amount of landing forces by teaching neuromuscular control of the lower limb during landing. The program was employed amongst fifteen female high school volleyball, basketball and soccer teams. The program was completed 3 days a week, 60-90 minutes a day for 6 weeks. Results after the 6 week program indicated that the training had a significant effect on the incidence of serious knee injury as the incidence of knee injury (per 1000 exposures) was 0.43 in the untrained group, 0.12 in the trained group, and 0.09 in the male control group. The trained group also had a significantly lower rate of noncontact injuries (0) than the untrained group (0.35). Results from these studies indicate that neuromuscular training may decrease injury risk in female athletes.

PLYOMETRICS

The practice of using plyometric exercises to improve strength and power has been utilized for a long time. However their benefits to athletes has only recently started to be studied in the past three decades. The term plyometrics has only been used since the mid-1960's to 1970's, but the pioneers of plyometrics were probably track and field athletes in the 1920's and 30's.[49] Any exercise can be considered plyometric if the muscle is preloaded with an eccentric contraction and then follow it quickly with a concentric contraction. Plyometric exercises cover a wide range of difficulties and intensities.[25] They require little equipment, time and they are safe for both children and adults to perform.[23]

Plyometric exercises are based on the premise that increasing the eccentric preload on a muscle induces the myostatic stretch reflex and potentially cause a more forceful contraction.[25] The mechanism underlying all plyometric exercises is the stretch-shortening cycle. This cycle is divided into three phases. Phase I is the prestretch/eccentric power phase, where there is forceful lengthening of the contracted muscle, and joint loads are absorbed and stored in the tenomuscular unit. During the second phase there is a brief period of time after the eccentric loading where the muscle length does not change. Then a concentric muscle contraction occurs during the third phase. The resulting powerful muscle contraction is developed by combining the stored elastic energy with voluntary and reflexive muscle activation.[50]

Studies have shown that plyometric jump-training can safely and effectively improve lower body strength and power in female athletes.[22] Plyometrics have also been used successfully in rehabilitation programs for lower extremity musculoskeletal injuries. Using plyometric exercises in rehabilitation promotes the use of efficient, functional motor patterns and promotes dynamic joint stabilization.[24]

Hewett et al.[22] tested the effects of a plyometric exercise program on female athletes and their landing mechanics and lower extremity strength. The authors designed the exercise program to teach neuromuscular control to the lower extremities, and therefore decrease the amount of landing forces felt by the body, and to increase the strength of the muscles surrounding the knee joint, to increase the stability of the joint. Eleven high school volleyball players participated in the jump-training program. The training sessions lasted 2 hours a day, 3 days a week, over the course of 6 weeks. The athletes were also required to perform a stretching program before performing the plyometric exercises, and weight-training program after completing the exercises.

Before and after completion of the 6-week jump-training program, the subjects underwent vertical jump height testing, muscle strength testing and force testing. The force testing was completed by having the athletes complete a simulated volleyball block jump and landing on a force plate. The jumps were analyzed for peak forces at landing, jump height, joint angles, and joint moments. Muscle strength was recorded on an isokinetic dynamometer at a speed of 360 °/sec. A control group of nine male subjects were also tested in the same manner.

The results of the testing indicated that ten of the eleven subjects decreased their landing forces by an average of 456 N. Hamstring peak torque and average power, and hamstring to quadriceps ratio all increased after training. The subjects also exhibited a 9.2% increase in vertical jump height after completing the training program.

Knee abduction and adduction moments decreased significantly after training, which suggests that the muscular control of the lower extremity was altered in the coronal plane. However, peak landing flexion and extension moments did not change with training, nor did the knee flexion angles. When compared with the male control group angles, the males did not differ as much as the investigators thought they would. Landing forces have been thought to decrease with increased knee flexion, the results of this study do not indicate that the angle of knee flexion is the most important factor in decreasing peak landing forces after training.

Witzke and Snow[25] investigated the effects of a nine month plyometric training program on the bone mineral content, lower extremity performance and static balance in adolescent girls. Twenty-five girls performed the plyometric training program three times a week for 30-45 minutes. The plyometrics consisted of hopping, jumping, bounding and box depth jumps. Data on bone mineral content, strength, and static balance was recorded at baseline and nine months. The results indicated that plyometric training improved trochanteric bone mineral content, leg strength, and balance in adolescent girls. The percent change in static balance from zero was significantly greater in those girls who were in the plyometric training program. The medial/lateral direction increased 29%, and the anterior/posterior direction increased 17%, in the girls participating in the jump training program. The authors attributed this difference to the plyometric drills activating the muscles and neural pathways involved in hip abduction and adduction, and knee and ankle stabilization.

Other research studies that examined the effects of plyometric training programs used various techniques, durations and populations, and had different purposes. Two studies observed improved running economy in participants of a plyometric training program.[51, 52] Plyometrics also brought about improvements in proprioception, kinesthesia and contractile strength of the rotator muscles of the shoulder in female swimmers.[53] The onset of fatigue during vertical jumping was delayed in the plyometric training group particpants when compared to a group that completed a weight training program.[54] Improvement was also found after completing a plyometric training program with peforming drills that measured acceleration, speed, coordination, dynamic balance, agility, lateral movement, and explosive power.[55] However, no differences were found between the plyometric and control groups in performing a freestyle tumble turn.

Chapter 3

METHODS

Subjects

Twenty-five female subjects (height= 167.69 $\pm$ 6.91 cm, weight= 59.81$\pm$ 9.37 kg, age= 20.32 $\pm$ 1.99 years) volunteered to participate in this research study. Participants had no history of diagnosed knee or ankle injury in either limb, no coexisting concussions, and were required to be physically active 3 days a week, but not currently participating in strength training for the past 2 months. Fifteen participants were selected to participate in the plyometric training program, while the other fifteen participants were placed in the control group. Randomization of group placement was not feasible due to availability of some participants. Four of the participants in the plyometric group dropped out over the course of the study for various reasons, such as an outside injury and time. Also, one control subject could not complete all of the testing sessions because of illness. This gave a total of 11 participants in the plyometric group, and 14 in the control group. The subjects that participated in the plyometric training program were compensated fifty dollars for their time, while the control group subjects received ten dollars.

The plyometric training program started with an information session held for all the potential subjects to explain the purpose and process of the study. Upon agreement of participation, the subjects were asked to read and sign an informed consent form, which was approved by the Michigan State University Committee on Research Involving Human Subjects (see Appendix A). All subjects were given a copy of the Paffenbarger Physical Activity Questionnaire[56] to complete before and after the completion of the study to determine their level of physical activity. The questionnaire collects information about the type and intensity of activities done in the past 2 weeks, and produces a kcal total. A questionnaire was used to obtain height, weight, leg dominance, and previous sport experience.

Plyometric training program

The training program consisted of thirteen plyometric exercises, varying in difficulty and intensity. Appendix B includes a detailed description of the program and individual jumps. This plyometric training program was adapted from Hewett et al.[22] An instructor taught the first session, and explained and demonstrated the proper technique for performing each jump. Emphasis was placed on identifying the correct posture, and the correct take-off and landing positions. A handout detailing the program was given to each subject. The contents of the paper described each jump, and gave instructions on the length of time for each jump and how to increase the intensity each week. The subjects were required to perform the training program for 45 to 60 minutes, 3 days a week, on alternating days, for 6 weeks under the supervision of the investigator.

Testing

All of the subjects were required to attend four testing sessions: one prior to the start of the training program, and one after weeks two, four and six of the training program. Before testing, all participants went through a warm-up of 5 minutes of jogging and skipping, and then lower body stretching.

Postural control measurements were made using an AMTI Accusway force plate (AMTI Inc., Watertown, MA) utilizing SWAYWIN software (AMTI Inc., Watertown, MA.). Subjects performed 3 trials for 30 seconds each on their dominant leg. The participant's dominant leg was determined by the asking which foot they would use to kick a soccer ball. The subjects were positioned on the force plate with the foot of their dominant leg in the middle, and then stood on their dominant leg with eyes open and arms crossed in front of them. They were told to focus on a target on the wall in front of them and remain as still as possible. (Appendix C)

Data were collected at 200 Hz, and the force plate was calibrated before each testing session. Dependent measures were mean center of pressure excursion velocity in the frontal and sagittal planes (VAvg), total length of path pressure (PLength), and the area of the 95% confidence ellipse formed by the center of pressure excursion (Area95). These variables are defined as:

Average velocity (Vavg): the distance of the center of pressure traveled divided by the time interval

Area of the 95% ellipse (Area95): area of the 95% confidence ellipse formed by the center of pressure excursion

Path length (Plength): total length of the center of pressure during the time interval

Hamstring and quadriceps strength of each subject's dominant leg was assessed using an isokinetic dynamometer (Biodex Inc., Shirley, NY). Participants were positioned on the dynamometer with their trunk perpendicular to the floor, hips flexed to

90°, and the knees flexed to 90°. The rotational axis of the dynamometer was aligned with the lateral femoral condyle. The participants were secured with a thoracic strap, waist strap, thigh strap, and a shin strap that was positioned one finger length above the lateral malleolus. (Appendix C)

Gravity correction was obtained by measuring the amount of torque placed on the dynamometer with the knee in a relaxed state at 45° of flexion. Two sets of ten repetitions of concentric flexion and extension at 60°/sec and 120°/sec were performed on the subject's dominant leg, with one minute rest given in between sets. Five practice repetitions were performed before the testing of each new speed. During the testing, the participants were required to fold their arms across their chest, were given verbal encouragement from the researcher. Dependent measures were peak torque (PeakTq), average peak torque (AvgPkTq), and average power (AvgPower) generated by the muscle groups during concentric flexion and extension. These variables are defined as:

Peak torque- PeakTq- highest amount of force generated by muscle contraction through the range of motion

Average peak torque- AvgPkTq- average torque produced through the range of motion

Average power- AvgPower- total amount of work divided by the total time of the work

Statistical Analysis

For each dependent variable of postural control (VAvg, Area95, and PLength), and isokinetic strength (PeakTq, AvgPkTq, and AvgPower), a one-between (group) and a one-within (time) repeated-measures analysis of variance (ANOVA) was used. The between subjects factor was grouped with 2 levels (experimental, control), while the within-subjects factor of time contained 4 levels (baseline, 2 weeks, 4 weeks, 6 weeks). Tukey post hoc analyses were performed for all significant interactions. Level of significance ($P < .05$) was set a priori for all statistical analyses. Analyses were performed with SPSS 10.0 (SPSS Inc., Chicago, IL) statistical software package.

The subject number was first calculated using a power of .8 and a moderate effect size of .6, and the subject number came out to be 63 subjects per group, but due to cost and time constraints this number would not be feasible. Previous research studies that studied ACL prevention programs used various subject group sizes. Hewett et al.'s first study consisted of 11 females in the test group and nine males in the control group. The second study used 15 trained female high school teams, 15 untrained female high school teams and 13 untrained male teams. Caraffa et al.[19] had 20 soccer teams in both their test and control groups, while Ettlinger et al.[20] had 20 ski areas in their test group and 22 ski areas in their control group. Other related studies used smaller subject populations, such as Rozzi et al.'s study[57] on knee joint laxity and neuromuscular characteristics consisted of 17 female and 17 male subjects. Also, Aagaaard et al.'s study[58] on isokinetic hamstring to quadriceps ratio used 4 female and 5 male subjects.

Chapter 4

RESULTS

Group Comparisons

ANOVA revealed no significant main effects or interaction effects for the amount of kcal burned per week ($F_{1,23}$ = 2.851, P = .105, 1-β = .634) which was calculated from the Paffenbarger Physical Activity Questionnaire. This indicates that the groups were equal in their activity levels at the beginning and end of the study. Also, there were no statistically significant differences between the plyometric and control groups at the first testing session of the strength and postural control variables. Therefore, the groups were equivalent in their quadriceps and hamstring strength, and balance at the beginning of the research study.

Postural Control

ANOVA revealed that there were group x time interaction for all of the postural control variables, VAvg ($F_{2,46}$ = .137, P = .873, 1-β = .930), Area95 ($F_{2,46}$ = .718,P = .493, 1-β = .836) and PLength ($F_{2,46}$ = .145, P = .866, 1-β = .929). Since no significant interactions found for these variable, this indicates that the values for average velocity, area of the 95% ellipse and path length were similar between pre and post measurements for both the plyometric and control groups. However there were some trends seen in the means of the data. The descriptive statistics show an overall slight decrease in velocity average and path length values across both groups, while the values for the area of the 95% ellipse slightly increased over the testing sessions for both groups.

Strength

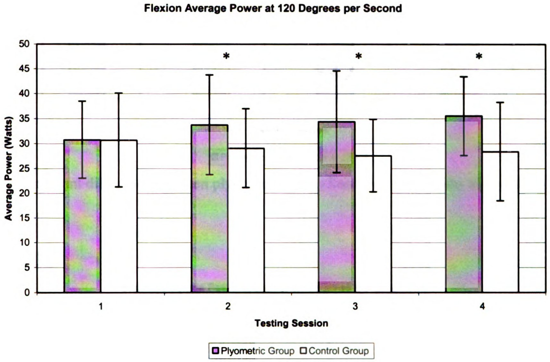
For the strength variables at 60 °/sec, ANOVA revealed no significant differences between the groups over time, for PeakTq- extension ($F_{3,69}$ = .080, P = .971, 1-β = .936), PeakTq- flexion ($F_{3,69}$ = .774, P = .512, 1-β = .792), AvgPkTq- extension ($F_{3,69}$ = .822, P = .486, 1-β = .781), AvgPkTq- flexion ($F_{3,69}$ = .748, P = .527, 1-β = .798), AvgPower-extension ($F_{3,69}$ = .177, P = .912, 1-β = .919), and AvgPower-flexion ($F_{3,69}$ = 1.553, P = .209, 1-β = .608).

No significant interactions were found at 120 °/sec for PeakTq- extension ($F_{3,69}$ = 1.397, P = .251, 1-β = .645), AvgPkTq-extension ($F_{3,69}$ = .572, P = .636, 1-β = .838), AvgPkTq- flexion ($F_{3,69}$ = 2.138, P = .103, 1-β = .477), and AvgPower- extension ($F_{3,69}$ = 2.706, P = .052, 1-β = .366).

There was a significant group x time interactions for the strength values at 120°/sec of PeakTq- flexion ($F_{3,69}$ = 3.162, P = .030) and AvgPower- flexion ($F_{3,69}$ = 3.487, P = .020). Effect sizes were calculated as .38 for PeakTq and .72 for AvgPower. Post hoc analysis revealed that there were significant differences between the plyometric and control groups for average power at testing sessions two, three and four.(Figure 1.1) A significant difference also existed between the first and last testing sessions of the plyometric group.

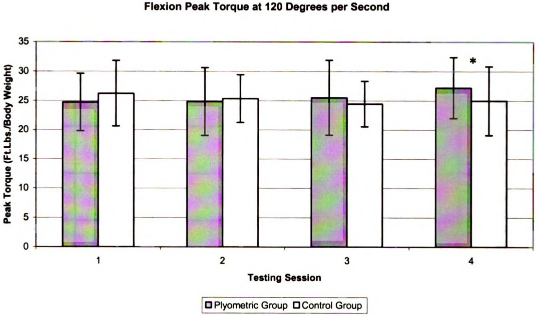
There was a significant difference between the means of the first and last testing sessions for the plyometric group for peak torque-flexion.(Figure1.2) The plyometric group was able to increase their peak torque with each session, while the control group's peak torque decreased with the first 3 sessions and then increased slightly. This same trend can be seen in average peak torque of flexion at 120 °/sec, however there was not a significant difference.(Figure 1.3)

Figure 4.1



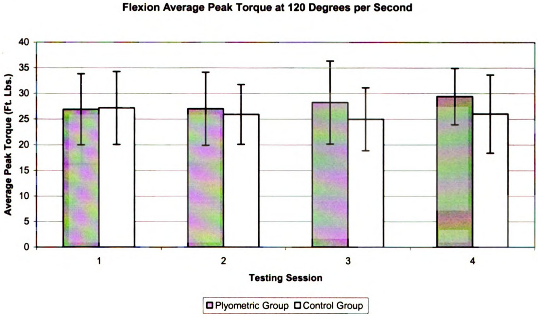
* Significantly different than the control group ($P = .020$)

Figure 4.2



* Significant difference between plyometric group Session 1 vs. Session 4 ($P = .030$)

Figure 4.3



Descriptive Statistics

Table 4.1

Descriptive Statistics for Peak Torque of Extension at 60°/sec

Test Session	PlyometricGroup(1)/ Control Group(2)	Mean	Standard Deviation	Number
1	1	74.3091	10.8385	11
	2	72.2250	10.9181	14
	Total	73.1420	10.7066	25
2	1	66.8636	11.1093	11
	2	66.1607	11.3582	14
	Total	66.4700	11.0195	25
3	1	64.5773	9.2379	11
	2	63.6214	8.0072	14
	Total	64.0420	8.3977	25
4	1	63.0000	9.8426	11
	2	62.0464	10.1944	14
	Total	62.4660	9.8434	25

Table 4.2

Descriptive Statistics for Peak Torque of Flexion at 60°/sec

Test Session	PlyometricGroup(1)/ Control Group(2)	Mean	Standard Deviation	Number
1	1	38.2000	5.4453	11
	2	36.7607	6.4891	14
	Total	37.3940	5.9746	25
2	1	36.6000	7.7359	11
	2	35.4214	5.8536	14
	Total	35.9400	6.6220	25
3	1	35.8182	6.7663	11
	2	33.6571	5.2549	14
	Total	34.6080	5.9357	25
4	1	37.6182	5.8745	11
	2	33.9321	5.6383	14
	Total	35.5540	5.9234	25

Table 4.3

Descriptive Statistics for Peak Torque of Extension at 120°/sec

Test Session	PlyometricGroup(1)/ Control Group(2)	Mean	Standard Deviation	Number
1	1	46.4318	8.0625	11
	2	47.6143	9.6321	14
	Total	47.0940	8.8147	25
2	1	46.6364	5.1655	11
	2	46.5821	8.9485	14
	Total	46.6060	7.3819	25
3	1	48.1500	6.0548	11
	2	45.3964	7.9106	14
	Total	46.6080	7.1496	25
4	1	47.9545	4.5856	11
	2	44.9143	7.4745	14
	Total	46.2520	6.4340	25

Table 4.4

Descriptive Statistics for Peak Torque of Flexion at 120°/sec

Test Session	PlyometricGroup(1)/ Control Group(2)	Mean	Standard Deviation	Number
1	1	24.7182	4.8561	11
	2	26.2250	5.5731	14
	Total	25.5620	5.2185	25
2	1	24.8273	5.8097	11
	2	25.3464	4.1007	14
	Total	24.1180	4.8209	25
3	1	25.5091	6.4140	11
	2	24.4464	3.8821	14
	Total	24.9140	5.0591	25
4	1	27.2000	5.1688	11
	2	24.9607	5.8520	14
	Total	25.9460	5.5650	25

Table 4.5

Descriptive Statistics for Average Peak Torque of Extension at 60°/sec

Test Session	PlyometricGroup(1)/ Control Group(2)	Mean	Standard Deviation	Number
1	1	86.8818	16.9320	11
	2	79.5321	18.1206	14
	Total	82.7660	17.6403	25
2	1	76.3091	16.6114	11
	2	73.0393	16.3586	14
	Total	74.4780	16.2071	25
3	1	76.1636	16.2831	11
	2	69.9571	14.5243	14
	Total	72.6880	15.3176	25
4	1	77.1864	12.3436	11
	2	69.9893	14.8307	14
	Total	73.1560	13.9972	25

Table 4.6

Descriptive Statistics for Average Peak Torque of Flexion at 60°/sec

Test Session	PlyometricGroup(1)/ Control Group(2)	Mean	Standard Deviation	Number
1	1	44.5000	7.9678	11
	2	40.7000	9.7219	14
	Total	42.3720	9.0197	25
2	1	41.1273	6.6255	11
	2	37.3464	8.0385	14
	Total	39.0100	7.5472	25
3	1	40.5000	8.0277	11
	2	35.9214	8.3912	14
	Total	37.9360	8.3888	25
4	1	42.9500	6.4281	11
	2	36.7714	9.0229	14
	Total	39.4900	8.4329	25

Table 4.7

Descriptive Statistics for Average Peak Torque of Extension at 120°/sec

Test Session	PlyometricGroup(1)/ Control Group(2)	Mean	Standard Deviation	Number
1	1	53.0273	15.8463	11
	2	48.9821	14.1807	14
	Total	50.7620	14.7564	25
2	1	52.9091	14.0126	11
	2	48.2071	11.6908	14
	Total	50.2760	12.7091	25
3	1	53.0409	12.4472	11
	2	46.5036	11.6744	14
	Total	49.3800	12.2209	25
4	1	54.2909	9.0728	11
	2	47.0571	9.3090	14
	Total	50.2400	9.7298	25

Table 4.8

Descriptive Statistics for Average Peak Torque of Flexion at 120°/sec

Test Session	PlyometricGroup(1)/ Control Group(2)	Mean	Standard Deviation	Number
1	1	26.8909	6.9059	11
	2	27.1536	7.0529	14
	Total	27.0380	6.8435	25
2	1	27.0136	7.1367	11
	2	25.9000	5.8479	14
	Total	26.3900	6.3296	25
3	1	28.2409	8.1387	11
	2	24.9821	6.0551	14
	Total	26.4160	7.0841	25
4	1	29.4045	5.4693	11
	2	26.0107	7.5721	14
	Total	27.5040	6.8174	25

Table 4.9

Descriptive Statistics for Average Power of Extension at 60°/sec

Test Session	PlyometricGroup(1)/ Control Group(2)	Mean	Standard Deviation	Number
1	1	58.4136	11.4264	11
	2	53.7786	12.1238	14
	Total	55.8180	11.8124	25
2	1	51.8409	10.2496	11
	2	47.5893	11.0197	14
	Total	49.4600	10.6859	25
3	1	51.3636	9.7106	11
	2	47.0464	10.1631	14
	Total	48.9460	10.0011	25
4	1	51.8273	7.6993	11
	2	46.3321	9.4870	14
	Total	48.7500	9.0112	25

Table 4.10

Descriptive Statistics for Average Power of Flexion at 60°/sec

Test Session	PlyometricGroup(1)/ Control Group(2)	Mean	Standard Deviation	Number
1	1	32.2773	6.2209	11
	2	27.7393	7.0592	14
	Total	29.7360	6.9572	25
2	1	29.5818	5.5766	11
	2	25.5679	5.8730	14
	Total	27.3340	5.9814	25
3	1	29.5227	5.8344	11
	2	23.5429	5.5100	14
	Total	26.1740	6.3092	25
4	1	31.1182	5.2427	11
	2	24.3214	6.2223	14
	Total	27.3120	6.6544	25

Table 4.11

Descriptive Statistics for Average Power of Extension at 120°/sec

Test Session	PlyometricGroup(1)/ Control Group(2)	Mean	Standard Deviation	Number
1	1	62.9591	11.6672	11
	2	61.5393	17.1328	14
	Total	62.1640	14.7049	25
2	1	68.0455	16.8551	11
	2	59.4429	13.9794	14
	Total	63.2280	15.5956	25
3	1	68.2864	13.6838	11
	2	58.3000	15.6601	14
	Total	62.6940	15.3770	25
4	1	68.4773	9.4694	11
	2	58.0750	12.5607	14
	Total	62.6520	12.2717	25

Table 4.12

Descriptive Statistics for Average Power of Flexion at 120°/sec

Test Session	PlyometricGroup(1)/ Control Group(2)	Mean	Standard Deviation	Number
1	1	30.7636	7.6975	11
	2	30.6964	9.4118	14
	Total	30.7260	8.5247	25
2	1	33.7636	9.9717	11
	2	33.7636	7.8741	14
	Total	31.1340	8.9819	25
3	1	34.4000	10.2464	11
	2	27.5786	7.3306	14
	Total	30.5800	9.2085	25
4	1	35.5591	7.9293	11
	2	28.3857	9.9483	14
	Total	31.5420	9.6443	25

Table 4.13

Descriptive Statistics for Average Velocity

Test Session	PlyometricGroup(1)/ Control Group(2)	Mean	Standard Deviation	Number
1	1	1.6127	.3554	11
	2	1.6607	.2892	14
	Total	1.6396	.3139	25
2	1	1.5021	.4427	11
	2	1.5598	.1786	14
	Total	1.5344	.3159	25
4	1	1.4045	.2178	11
	2	1.4986	.2625	14
	Total	1.4572	.2437	25

Table 4.14

Descriptive Statistics for Area of the 95% Ellipse

Test Session	PlyometricGroup(1)/ Control Group(2)	Mean	Standard Deviation	Number
1	1	.8888	.1924	11
	2	.8426	.2086	14
	Total	.8629	.1989	25
2	1	.8827	.2587	11
	2	.9571	.3634	14
	Total	.9244	.3176	25
4	1	.9373	.2934	11
	2	.9174	.3276	14
	Total	.9261	.3067	25

Table 4.15

Descriptive Statistics for Path Length

Test Session	PlyometricGroup(1)/ Control Group(2)	Mean	Standard Deviation	Number
1	1	48.4276	10.5785	11
	2	49.8379	8.6512	14
	Total	49.2173	9.3636	25
2	1	45.0494	13.2827	11
	2	46.7776	5.3626	14
	Total	46.0172	9.4793	25
4	1	42.1436	6.5158	11
	2	44.9764	7.8950	14
	Total	43.7300	7.3152	25

Chapter 5

DISCUSSION

Previous research has looked at the trends in, possible risk factors for, and potential prevention programs for female ACL injuries. The purpose of this research study was to examine the effects of a plyometric jump training program on the neuromuscular characteristics in female athletes, specifically postural control, and hamstring and quadriceps strength. After the completion of a six week plyometric program, the plyometric group participants significantly increased their average power and peak torque during concentric flexion at 120°/sec. No differences were found for the postural control variables of VAvg, Area95, PLength, or other strength variables AvgPkTq, AvgPower, and PeakTq at 60°/sec, and AvgPkTq at 120°/sec.

Effects of Plyometrics on Strength

The results of this research study support the hypothesis that plyometric jump training exercises improved the strength of female athletes. Significantly increased peak torque and average power values were found during flexion for the plyometric group at the speed of 120°/sec. The same trend was also seen for average peak torque, although it did not reach statistical significance. However, no significant differences were seen in the strength variables between the plyometric and control groups at 60°/sec and extension at 120°/sec.

The plyometric group improved their hamstring average power over the course of the plyometric training program, while the control group decreased slightly. Average power is the total amount of work divided by the total movement time, and indicates how quickly the muscle can produce force. The plyometric jumps seem to have resulted in the females' hamstring muscles to being able to produce more work in the same amount of time.

A significant difference was also observed between the first and last testing sessions in the plyometric group for peak torque at 120°/sec. The plyometric group increased their peak torque during the plyometric training program, while the control group slightly decreased their peak torque. Peak torque refers to the highest amount of force the joint was able to generate by muscle contraction throughout the range of motion. The females in the plyometric group were able to generate a greater force using their hamstring muscles as they progressed through the plyometric training program.

The same trend was also seen for average peak torque for flexion at 120°/sec. The plyometric group improved over time, while the control group experienced a slight decrease in average peak torque. Though the differences were not statistically significant across the testing sessions, these values show that the plyometric group participants were able to generate more hamstring force as they advanced in the plyometric training.

The strength gains observed in this study can be compared to the results found by Hewett et al.[22], which showed increases in hamstring isokinetic peak torque and average power after plyometric training. Concentric hamstring strength was measured on a Biodex isokinetic dynamometer at a speed of 360°/sec. The participants in their study performed the plyometric program in conjunction with a weight training program, which may have contributed to the strength gains that were seen. The current study did not use a weight training program, and significant strength gains were still able to be seen in the hamstrings.

No effect was seen on the concentric strength of the quadriceps muscle group throughout the plyometric program, which is different than the findings of Witzke and Snow[25], who observed that knee extensor strength improved in adolescent girls who participated in a plyometric training program. However, the improvement in strength was not significantly different from the improvements in the control subjects. The plyometric were performed over the course of a 9-month school year, and the participants were adolescent girls with a mean age of 14.6. The longer duration of the plyometric program and younger ages of the participants may have produced the improved quadriceps strength that was not seen in this study.

The plyometric jumps had a positive effect on the concentric strength of the hamstring muscles, even though the jumps repeatedly used the eccentric actions of the hamstring muscles. Eccentric muscle actions can develop greater maximum forces than concentric or isometric muscle actions[59], and therefore have been thought to be able to be more successful at increasing overall strength.[60] Various research studies have compared the effectiveness of eccentric and concentric training on increasing muscular strength. In relation to the current study where eccentric training resulted in concentric strength gains, eccentric training has been shown to produce similar[61-63], greater[64, 65], or no[66, 67] increase in concentric strength. The benefits from eccentric training have been attributed to increased neural activation[65, 67] and greater muscle hypertrophy[67], and more specifically hypertrophy of type II muscle fibers[68].

The increase in concentric hamstring strength combined with the maintained quadricep strength increases the females' hamstring to quadriceps ratio. A decreased hamstring to quadriceps ratio has been shown to be more common in female athletes, and associated with a higher injury risk.[9] By improving a female's hamstring to quadriceps ratio, this may also decrease her risk of injury. The hamstrings are important in controlling anterior tibial translation. Female athletes have been shown to activate their quadriceps muscle group first when responding to anterior tibial translation.[11] This action adds further strain to the ACL by pulling more anteriorly on the tibia. Improved hamstring strength can help to counteract this action and reduce the strain placed on the ACL.

Hewett et al.[22] also saw an increase in hamstring and quadriceps ratio after their plyometric training program. When compared to the ratio of the male controls in their study, the trained females' ratios were almost equivalent. The plyometric training program was used in conjunction with weight training program, which may have influenced the strength gains.

Effects of Plyometrics on Postural Control

This study suggests postural control is not improved in female athletes who participate in a plyometric training program. There was an overall decrease in mean scores across the variables for both the plyometric and control groups, which indicates improved postural control in all participants. However, this trend may have been caused by a familiarity with the testing procedures.

Unlike the results of this research study, Witzke and Snow[25] observed significant improvements in static balance in the adolescent girls who participated in the 9 month plyometric training program. Static balance was determined by using a Biodex Stabilometer, which was assessed in degrees of deviation in the anterior/posterior and medial/lateral directions. The medial/lateral balance improved 29%, while the anterior/posterior stability increased 17%. The authors attributed this improvement to the plyometric drills that incorporated lateral movements, which exercised the muscles and neural pathways involved in controlling hip abduction and adduction, and knee and ankle stabilization. The different postural control testing measures, length of plyometric training programs, or mean ages of participants may have resulted in conflicting results between the two studies.

Similar to the current study, Blackburn et al.[12] found that the effects of proprioception and strength training programs had little effect on static balance. No improvements were seen in static balance after 6 weeks of training. Balance was measured by using a force plate, as it was in the current study. The authors attributed these results to static balance not being very challenging to healthy subjects. All of their subjects, as well as the subjects in this research study, had properly functioning visual, vestibular, and somatosensory systems, which contribute to postural control.

In the same Blackburn et al. study[12], significant improvements were found in all of the training groups for semidynamic and dynamic balance. Semidynamic balance was assessed using a Biodex Stability System, and dynamic balance with a modified version of the Bass Test of Dynamic Balance. All of the training groups showed significant differences between pre- and post- testing. The current research study did not employ testing measures for semidynamic or dynamic balance, only static balance measures were taken.

Clinical Implications

To date, only a couple of research studies[18, 20, 21] have investigated the effects of ACL prevention programs on female athletes. This study observed the effects of a plyometric training program on two possible ACL risk factors, postural control, and hamstrings and quadriceps strength. The plyometric training program had a significant effect on the hamstring strength of the female participants. The increased hamstring strength shows that plyometric training may be a good program for young females to utilize to improve hamstring strength, a risk factor for ACL injury.

The results of this research study support the implementation of a plyometric training program by coaches, athletic trainers, and strength training coaches in the daily routine of their female athletes. The plyometric training program also exposes the females to landings from a jump during the exercises. Noncontact mechanisms, such as landing from a jump, are the most common mechanism for ACL injury.[32] This aspect of plyometric training is also important in addition to the increased hamstring to quadriceps ratio.

The plyometric training program used in this study is relatively easy and quick to apply to a female athlete's exercise program. The program consisted of a warm-up, a series of 7 to 8 jumps, and a cool-down, and was about 45 minutes long in duration. The series of jumps would be simple to add to the pre-practice routine of, and to teach to female athletes. The drills do not require any special equipment, other than a cone, and can easily be done in a gymnasium.

Considerations for Future Research

Research should be continued on the various prevention programs and their effect on female ACL injuries. Suggestions for further research are:

1) The effects of plyometrics on other ACL risk factors, such as ground reaction forces and muscle activation patterns;

2) The effects of a plyometric training program on the eccentric strength of the quadricep and hamstring muscle groups;

3) The effects of a plyometric training program on semidynamic and dynamic balancing;

4) Comparison of female and male hamstring strength gains after participation in a plyometric training program;

5) Comparison of female strength gains between plyometric training programs of varying lengths and jumps.

Limitations

The small sample size contributes to the low power of the study. Each of the groups started out with fifteen subjects, but due to dropouts, eleven finished the plyometric training program and fourteen finished in the control group. A larger sample size would have been ideal, but due to time and cost restrictions, was not feasible.

Balance data could not be measured during the third testing session for all of the participants in the study. The force plate was not functioning properly during each of the trials; therefore about half of the participants did not get tested. The statistical analyses were run on the data from the first, second and fourth testing sessions.

APPENDIX A

INFORMED CONSENT FORM

Title of project: The Effects of Plyometric Training on Neuromuscular Characteristics in Female Athletes

1. This section provides an explanation of the study in which you will be participating:

   a. The study in which you will be participating is part of research intended to develop a plyometric jump training program that may prevent anterior cruciate ligament tears sustained by female athletes. Plyometric training programs are used to develop an explosive movement over a short period of time. Plyometric exercises involve hops, bounds, and jumps to strengthen the lower extremity and to develop explosive power. The exercises induce a rapid stretch on the muscles, followed immediately by a rapid concentric contraction.

   b. If you agree to take part in this research, you will undergo a battery of tests on 4 separate days. Testing will be performed at the beginning of the study, after week 2, after week 4, and after week 6. If you are assigned to the experimental training group, you will be required to perform a plyometric jump training program 3 days a week, on alternating days, for 6 weeks. This training program will consist of a variety of plyometric exercises and will take approximately 45 minutes to complete.

   Performance testing will consist of assessment of postural control and isokinetic strength. The protocol for each of these specific assessment modalities will be described.

   Postural control will be assessed using an AMTI Accusway balance platform. Subjects will perform 3 trials, 30 seconds each, of single leg balance, on their dominant limb, with their eyes open. Postural control measures the ability of the subject to balance. The platform will measure the changes in position of the subject's center of gravity as they balance on a single foot.

   Hamstring and quadriceps strength will be assessed using a Biodex isokinetic dynamometer. Subjects will perform 3 sets of 10 repetitions of concentric flexion and extension at 60°/sec and 120°/sec. During these repetitions, maximum resistance will be provided through out the range of motion by the machine, while the muscle contraction being performed is at a constant velocity, set by the machine. During an isokinetic contraction, the muscle length is changing while the contraction is performed at a constant speed.

c. Your participation in this research will take approximately 13 hours over the course of 6 weeks.

d. You should not experience any discomfort while participating in this study other than that which normally accompanies intense exercise.

e. You will receive financial compensation for participating in this study if you complete all of the required training and testing sessions. If you are selected to be in the plyometric group you will receive $50, and $10 if you are in the control group.

2. This section describes your rights as a research participant:

a. You may ask questions about the research procedures at any time, and/or discuss any questions regarding research related injuries. These questions and concerns should be directed to Angela DiPasquale at (517) 353-0892 (mornings) or (517) 203-4468 (evenings), or to Kavin Tsang at (517) 353-2010 (business hours). If you have questions regarding your role and rights as a research subject, you may contact the Institutional Review Board: Dr. Ashir Kumar, M.D. Chair, University Committee on Research Involving Human Subjects at (517) 355-2180.

b. Your participation in this study is confidential. Only the investigators will have access to your identity and to information that can be associated with your identity. If this research becomes published, no personally identifying information will be disclosed. To make sure your participation is confidential only a subject number will appear on your data collection sheet. The researchers will be the only ones that can match your name with your subject number. Your privacy will be protected to the maximum extent allowable by law.

c. Your participation is voluntary and you may stop participating at any time, or decline to answer any specific questions.

d. This study presents no risks to you beyond those associated with intense exercise.

e. Your participation in this study will potentially benefit those that may be predisposed to sustaining various injuries.

f. If you are injured as a result of your participation in this research project, Michigan State University will provide emergency medical care if necessary. If the injury is not caused by the negligence of MSU you are personally responsible for the expense of this emergency care and any other medical expenses incurred as a result of this injury.

3. This section indicates that you are giving your informed consent to participate in the research:

a. You agree to participate in the scientific investigation described above, as an authorized part of the education and research program of the Michigan State University.

b. You have been given the information, and have received answers to any questions that you may have had about the research procedure. You agree to the conditions of this study as described.

c. To the best of your knowledge and belief, you are not pregnant and have no physical or mental illness, or difficulties that would increase the risk of participation in this study. If at any time in the study, you feel that you might have become pregnant, please notify the investigators immediately and your participation in the research study will be discontinued.

d. You will receive financial compensation for participating in this study.

e. Your participation is voluntary and that you may withdraw from this study at any time by notifying the person in charge.

f. You are 18 years of age or older, and/or a full-time student of the Michigan State University.

g. You will receive a signed copy of this consent form.

______________________________________ _______________

Signature Date

Researcher:

I certify that the informed consent procedure has been followed, and I have answered any questions from the participant above as fully as possible.

______________________________________ ________________

Signature Date

APPENDIX B

PLYOMETRIC TRAINING PROGRAM

(adapted from Hewett et al.[22])

WEEK 1

1. Wall jumps	20 sec.
2. Tuck jumps	20 sec.
3. Broad jumps stick landing	5 reps
4. Squat jumps	10 sec.
5. Double leg cone jumps	30 sec. each (side/side, front/back)
6. 180° jumps	20 sec.
7. Bounding in place	20 sec.

WEEK 2

1. Wall jumps	25 sec.
2. Tuck jumps	25 sec.
3. Broad jumps stick landing	10 reps
4. Squat jumps	15 sec.
5. Double leg cone jumps	30 sec. each (side/side, front/back)
6. 180° jumps	25 sec.
7. Bounding in place	25 sec.

WEEK 3

1. Wall jumps	30 sec.
2. Tuck jumps	30 sec.
3. Jump, jump, jump, vert. jump	5 reps
4. Squat jumps	20 sec.
5. Double leg cone jumps	30 sec. each (side/side, front/back)
6. Scissor jump	30 sec.
7. Bounding for distance	1 run
8. Hop, hop, stick	5 reps/leg

WEEK 4

1. Wall jumps	30 sec.
2. Tuck jumps	30 sec.
3. Jump, jump, jump, vert. jump	8 reps
4. Squat jumps	20 sec.
5. Double leg cone jumps	30 sec. each (side/side, front/back)
6. Scissor jump	30 sec.
7. Bounding for distance	2 runs
8. Hop, hop, stick	5 reps/leg

WEEK 5

1.	Wall jumps	30 sec.
2.	Cone jumps	30 sec. each (side/side, front/back)
3.	Jump, jump, jump, vert. jump	8 reps
4.	Squat jumps	25 sec.
5.	Single-legged jumps distance	5 reps/leg
6.	Jump into bounding	3 runs
7.	Single-legged hop, hop, stick	5 reps/leg

WEEK 6

1.	Wall jumps	30 sec.
2.	Cone jumps	30 sec. each (side/side, front/back)
3.	Jump, jump, jump, vert. jump	10 reps
4.	Squat jumps	25 sec.
5.	Single-legged jumps distance	10 reps/leg
6.	Jump into bounding	5 runs
7.	Single-legged hop, hop, stick	10 reps/leg

DESCRIPTION OF JUMPS

1. 180° jumps- Two-footed jump. Rotate 180° in midair. Hold landing 2 seconds, then repeat in reverse direction.

2. Bounding for distance- Start bounding in place and slowly increase distance with each step, keeping knees high.

3. Bounding in place- Jump from one leg to the other straight up and down, progressively increasing rhythm and height.

4. Broad-jumps, stick landing- Two-footed jump as far as possible. Hold landing for 5 seconds.

5. Cone jumps- Double-leg jump with feet together. Jump side-to-side over cones quickly. Repeat forward and backward.

6. Hop, hop stick- Single-legged hop. Stick landing for 5 seconds. Increase distance of hop as technique improves.

7. Jump into bounding- Two-footed broad jump. Land on single leg, then progress into bounding for distance.

8. Jump, jump, jump, vertical jump- Three broad jumps with vertical jump immediately after landing the third broad jump.

9. Scissors jump- Start in stride position with one foot well in front of the other. Jump up, alternating foot positions in midair.

10. Single-legged jumps distance- One-legged hop for distance. Hold landing (knees bent) for 5 seconds.

11. Squat jumps- Standing jump raising both arms overhead, land in squatting position touching both hands to the floor.

12. Tuck jumps- From standing position jump and bring both knees up to chest as high as possible. Repeat quickly.

13. Wall jumps- With knees slightly bent and arms raised overhead, bounce up and down off toes.

PICTURES OF PLYOMETRIC JUMPS

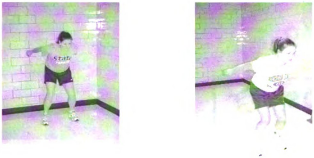
1. 180° jumps-



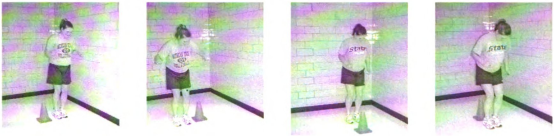
2. Bounding for distance-


3. Bounding in place-

4. Broad jumps



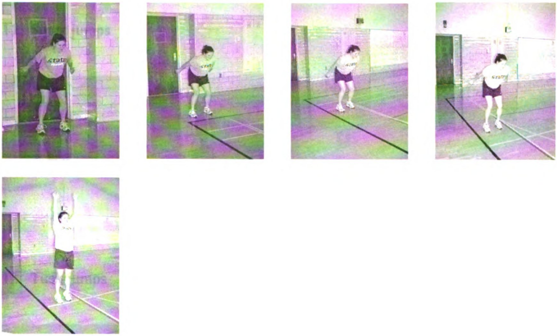
5. Cone jumps



6. Hop, hop stick

7. Jump into bounding

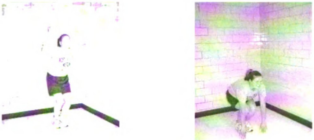
8. Jump, jump, jump, vertical



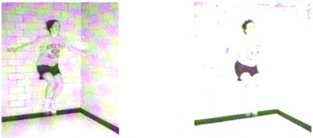
9. Scissors jump

10. Single-legged jumps distance

11. Squat jumps



12. Tuck jumps



13. Wall jumps

APPENDIX C

PICTURES OF TESTING INSTRUMENTS

AMTI Accusway Force Platform

Biodex Isokinetic Dynamometer

APPENDIX D

ANOVA TABLES

ANOVA Table for the Relationship of Time and Treatment to Postural Control Variables

Source	Measure	Sum of Squares	df	Mean Square	F	Sig.	Observed Power
Factor	VAvg	.425	2	.213	8.007	.001	.944
	Area95	.05579	2	.02790	.808	.452	.180
	PLength	385.673	2	192.837	8.120	.001	.947
Factor*TX	VAvg	.007262	2	.003631	.137	.873	.070
	Area95	.04954	2	.02477	.718	.493	.164
	PLength	6.868	2	3.434	.145	.866	.071
Error	VAvg	1.222	46	.02656			
	Area95	1.587	46	.03451			
	PLength	1092.376	46	23.747			

ANOVA Table for the Relationship of Time and Treatment to Strength Variables for Extension at 60°/sec

Source	Measure	Sum of Squares	df	Mean Square	F	Sig.	Observed Power
Factor	PeakTq	1659.027	3	553.009	18.744	.000	1.000
	AvgPkTq	1677.693	3	559.231	20.814	.000	1.000
	AvgPower	850.779	3	283.593	24.905	.000	1.000
Factor*TX	PeakTq	7.062	3	2.354	.080	.971	.064
	AvgPkTq	66.227	3	22.076	.822	.486	.219
	AvgPower	6.046	3	2.015	.177	.912	.081
Error	PeakTq	2035.694	69	29.503			
	AvgPkTq	1853.884	69	26.868			
	AvgPower	785.690	69	11.387			

ANOVA Table for the Relationship of Time and Treatment to Strength Variables for Flexion at 60°/sec

Source	Measure	Sum of Squares	df	Mean Square	F	Sig.	Observed Power
Factor	PeakTq	94.510	3	31.503	3.124	.031	.703
	AvgPkTq	260.229	3	86.743	8.309	.000	.990
	AvgPower	158.642	3	52.881	8.110	.000	.998
Factor*TX	PeakTq	23.431	3	7.810	.774	.512	.208
	AvgPkTq	23.423	3	7.808	.748	.527	.202
	AvgPower	30.387	3	10.129	1.553	.209	.392
Error	PeakTq	695.901	69	10.086			
	AvgPkTq	720.363	69	10.440			
	AvgPower	449.937	69	6.521			

ANOVA Table for the Relationship of Time and Treatment to Strength Variables for Extension at 120°/sec

Source	Measure	Sum of Squares	df	Mean Square	F	Sig.	Observed Power
Factor	PeakTq	4.635	3	1.545	.082	.969	.064
	AvgPkTq	20.156	3	6.719	.276	.842	.100
	AvgPower	29.581	3	9.860	.246	.864	.094
Factor*TX	PeakTq	78.753	3	26.251	1.397	.251	.355
	AvgPkTq	41.693	3	13.898	.572	.636	.162
	AvgPower	324.924	3	108.308	2.706	.052	.634
Error	PeakTq	1296.242	69	18.786			
	AvgPkTq	1677.641	69	24.314			
	AvgPower	2761.905	69	40.028			

ANOVA Table for the Relationship of Time and Treatment to Strength Variables for Flexion at 120°/sec

Source	Measure	Sum of Squares	df	Mean Square	F	Sig.	Observed Power
Factor	PeakTq	18.339	3	6.113	1.137	.340	.294
	AvgPkTq	23.088	3	7.696	.855	.469	.227
	AvgPower	21.801	3	7.267	.385	.764	.122
Factor*TX	PeakTq	50.984	3	16.995	3.162	.030	.709
	AvgPkTq	57.725	3	19.242	2.138	.103	.523
	AvgPower	197.615	3	65.872	3.487	.020	.756
Error	PeakTq	370.824	69	5.374			
	AvgPkTq	621.072	69	9.001			
	AvgPower	1303.274	69	18.888			

BIBLIOGRAPHY

1. Engstrom B, Johansson C, Tornkvist H. Soccer injuries among elite female players. *American Journal of Sports Medicine*. 1991;19:372-375.

2. Zillmer D, Powell J, Albright J. Gender-specific injury patterns in high school varsity basketball. *Journal of Women's Health*. 1992;1:69-76.

3. Chandy TA, Grana WA. Secondary school athletic injury in boys and girls: a three-year comparison. *The Physician and Sportsmedicine*. 1985;13:106-111.

4. Messina DF, Farney WC, DeLee JC. The incidence of injury in Texas high school basketball. A prospective study among male and female athletes. *The American Journal of Sports Medicine*. 1999;27:294-299.

5. Arendt E, Dick R. Knee injury patterns among men and women in collegiate basketball and soccer: NCAA data and review of literature. *The American Journal of Sports Medicine*. 1995;23:694-701.

6. Gray J, Taunton J, McKenzie D, Clement D, McConkey J, Davidson R. A survey of injuries to the ACL of the knee in female basketball players. *International Journal of Sports Medicine*. 1985;6:314-316.

7. Overend T, Lee W, Speechley M. Anterior cruciate ligament injuries in intercollegiate basketball players: A survey of gender difference. *Physiotherapy Canada*. 1999;51:22-26,43.

8. Griffin L, Agel J, Albohm M, et al. Noncontact anterior cruciate ligament injuries: Risk factors and prevention strategies. *Journal of the American Academy of Orthopaedic Surgery*. 2000;8:141-150.

9. Soderman K, Alfredson H, Pietila T, Werner S. Risk factors for leg injuries in female soccer players: A prospective investigation during one out-door season. *Knee Surgery, Sports Traumatology, and Arthroscopy*. 2001;9:313-321.

10. Moul JL. Differences in selected predictors of anterior cruciate ligament tears between male and female NCAA division I collegiate basketball players. *Journal of Athletic Training*. 1998;33:118-121.

11. Huston LJ, Wojtys EM. Neuromuscular performance characteristics in elite female athletes. *The American Journal of Sports Medicine*. 1996;24:427-436.

12. Blackburn T, Guskiewicz K, Petschauer M, Prentice W. Balance and joint stability: The relative contributions of proprioception and muscular strength. *Journal of Sport Rehabilitation*. 2000;9:315-328.

13. McGuire T, Greene J, Best T, Leverson G. Balance as a predictor of ankle injuries in high school basketball players. *Clinical Journal of Sports Medicine.* 2000;10:239-244.

14. Boden BP, Griffin LY, Garrett WEJ. Etiology and prevention of noncontact ACL injury. *The Physician and Sportsmedicine.* 2000;28:53-60.

15. Huston LJ, Greenfield MLVH, Wojtys EM. Anterior cruciate ligament injuries in the female athlete. Potential risk factors. *Clinical Orthopaedics and Related Research.* 2000:50-63.

16. Griffin L. The female athlete. In: DeLee J, Drez D, eds. *Orthopaedic Sports Medicine: Principle and Practice.* Philadelphia: Saunders; 1994:356-373.

17. Toth A, Cordasco F. Anterior cruciate ligament injuries in the female athlete. *Journal Gender Specific Medicine.* 2001;4:25-34.

18. Hewett TE, Lindenfeld TN, Riccobene JV, Noyes FR. The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. *The American Journal of Sports Medicine.* 1999;27:699-705.

19. Caraffa A, Cerulli G, Projetti M, Aisa G, Rizzo A. Preventioin of anterior cruciate ligament injuries in soccer. A prospective controlled study of proprioceptive training. *Knee Surgery, Sports Traumatology, Arthroscopy.* 1996;4:19-21.

20. Ettlinger CF, Johnson RJ, Shealy JE. A method to help reduce the risk of serious knee sprains incurred in alpine skiing. *The American Journal of Sports Medicine.* 1995;23:531-537.

21. Soderman K, Werner S, Pietila T, Engstrom B, Alfredson H. Balance board training: Prevention of traumatic injuries of the lower extremities in female soccer players? *Knee Surgery, Sports Traumatology, Arthroscopy.* 2000;8:356-363.

22. Hewett T, Stroupe A, Nance T, Noyes F. Plyometric training in female athletes. *American Journal of Sports Medicine.* 1996;24:765-773.

23. Chu D. Jumping into plyometrics. Champaign, IL: Human Kinetics; 1995.

24. Swanik C, Swanik K. Plyometrics in rehabilitating the lower extremity. *Athletic Therapy Today.* 1999;4:16-22.

25. Witzke KA, Snow CM. Effects of plyometric jump training on bone mass in adolescent girls. *Medicine and Science in Sports and Exercise.* 2000;32:1051-1057.

26. Ireland ML, Gaudette M, Crook S. ACL injuries in the female athlete. *Journal of Sport Rehabilitation.* 1997;6:97-110.

27. Arendt EA, Agel J, Dick R. Anterior cruciate ligament injury patterns among collegiate men and women. *Journal of Athletic Training*. 1999;34:86-92.

28. Wilk K. Still interesting after all these years. *Journal of Sport Rehabilitation*. 1997;6:79.

29. Arnheim D, Prentice W. Principles of Athletic Training. New York: McGraw Hill Higher Education; 2000.

30. More R, Karras B, Neiman R, Fritschy D, Woo S, Daniel D. Hamstrings-an anterior cruciate protagonist: and in vitro study. *American Journal of Sports Medicine*. 1993;21:231-237.

31. Palmitier R, An K, Scott S, Chao E. Kinetic chain exercise in rehabilitation. *Sports Medicine*. 1991;11:402-413.

32. Griffis N, Nequist S, et a. Injury prevention of the anterior cruciate ligament, abstracted. *American Orthopaedic Society for Sports Medicine: Meeting Abstracts, Symposia, and Instructional Courses. 15th Annual Meeting*. Traverse City, MI; 1989.

33. Noyes F, Moorar P, Matthews D, et a. The symptomatic anterior cruciate-deficient knee. Part 1: The long-term functional disability in athletically active individuals. *Journal of Bone and Joint Surgery*. 1983;65:154-162.

34. Ireland ML. Anterior cruciate ligament injury in female athletes: epidemiology. *Journal of Athletic Training*. 1999;34:150-154.

35. Moeller JL, Lamb MM. Anterior cruciate ligament injuries in female athletes. *The Physician and Sportsmedicine*. 1997;25:31-48, 54.

36. Baker MM. Anterior cruciate ligment injuries in the female athlete. *Journal of Women's Health*. 1998;7:343-349.

37. Dunnam L, Hunter G, Williams B, Dremsa C. Comprehensive evaluation of the University of Alabama at Birmingham women's volleyball training program. *National Strength and Conditioning Association Journal*. 1988;10:50-52.

38. Shultz S, Perrin D, Adams J, Arnold B, Gansneder B, Granata K. Neuromuscular response characteristics in men and women after knee perturbation in a single-leg, weight-bearing stance. *Journal of Athletic Training*. 2001;36:37-43.

39. Wilk K, Escamilla R, Fleisig G, Barrentine S, Andrews J, Boyd M. A comparison of tibiofemoral joint forces and electromyographic activity during open and closed kinetic chain exercises. *American Journal of Sports Medicine*. 1996;24:518-527.

40. Malinzak B, Colby S, Kirkendall D, Garrett W. Electromyographic and three-dimensional kinematic analysis of cutting manuevers in men and women: Implications for anterior cruciate ligament injury at footstrike. . *AOSSM Speciality Day*. Anaheim, CA; 1999.

41. Kreighbaum E, Barthels K. Linear momentum and kinetic energy. In: Kreighbaum E, Barthels K, eds. *Biomechanics: A qualitative approach for studying human movement*. Boston: Allyn and Bacon; 1996:291-293.

42. Gray-McNitt J. Kinetics of the lower extremities during drop landings from three heights. *Journal of Biomechanics*. 1993;26:1037-1046.

43. Hartley A. Practical Joint Assessment: A Sports Medicine Manual. St. Louis, MO: Mosby Year Book; 1990.

44. Bonci CM. Assessment and evaluation of predisposing factors to anterior cruciate ligament injury. *Journal of Athletic Training*. 1999;34:155-164.

45. Wilk K, Arrigo C, Andrews J, Clancy W. Rehabilitation after anterior cruciate ligament reconstruction in the female athlete. *Journal of Athletic Training*. 1999;34:177-193.

46. Wilk K, Zheng N, Fleisig G, Andrews J, Clancy W. Kinetic chain exercise: implications for the anterior cruciate ligament patient. *Journal of Athletic Training*. 1999;34:125-143.

47. Heitz N, Eisenman P, Beck C, Walker J. Hormonal changes throughout the menstrual cycle and increased anterior cruciate ligament laxity. *Journal of Athletic Training*. 1999;34:144-149.

48. Wojtys E, Huston L, Lindenfeld T, Hewett T, Greenfield M. Association between the menstrual cycle and anterior cruciate ligament injuries in female athletes. *The American Journal of Sports Medicine*. 1998;26:614-619.

49. Bompa T. Power training for sport. Buffalo: Mosaic Press; 1996.

50. Wilt F. Plyometrics, what it is and how it works. *Athletic Journal*. 1975;55:76-90.

51. Spurrs R, Murphy A, Watsford M. The effect of plyometric training on distance running performance. *European Journal of Applied Physiology*. 2003;89:1-7.

52. Turner A, Owings M, Schwane J. Improvement in running economy after 6 weeks of plyometric training. *Journal of Strength and Conditioning Research*. 2003;17:60-67.

53. Swanik K, Lephart S, Swanik B, Lephart S, Stone D, Fu F. The effects of shoulder plyometric training on proprioception and selected muscle performance characteristics. *Journal of Shoulder and Elbow Surgery*. 2002;11:579-586.

54. McLaughlin E. A comparison between two training programs and their effects on fatigue rates in women. *Journal of Strength and Conditioning Research*. 2001;15:25-29.

55. Dean W, Nishihara M, Romer J, Murphy K, Mannix E. Efficacy of a 4-week supervised training program in improving components of athletic performance. *Journal of Strength and Conditioning Research*. 1998;12:238-242.

56. Paffenbarger R, Wing A, Hyde R. Physical activity as an index of heart attack risk in college alumni. *American Journal of Epidemiology*. 1978;108:161-175.

57. Rozzi SL, Lephart SM, Gear WS, Fu FH. Knee joint laxity and neuromuscular characteristics of male and female soccer and basketball players. *The American Journal of Sports Medicine*. 1999;27:312-319.

58. Aagaard P, Simonsen E, Magnusson S, Larsson B, Dyhre-Poulsen P. A new concept for isokinetic hamstring: quadriceps muscle strength ratio. *The American Journal of Sports Medicine*. 1998;26:231-237.

59. Doss W, Karpovich P. A comparison of concentric, eccentric, and isometric strength of the elbow flexors. *Journal of Applied Physiology*. 1965;20:351-353.

60. Hakkinen K, Komi P. Effect of different combined concentric and eccentric muscle work regimens on maximal strength development. *Journal of Human Movement Studies*. 1981;7:33-44.

61. Ellenbecker T, Davies G, Rowinski M. Concentric versus eccentric isokinetic strengthening of the rotator cuff: objective data versus functional test. *American Journal of Sports Medicine*. 1988;16:64-69.

62. Johnson B, Adamczyk J, Tennoe K, Stromme S. A comparison of concentric and eccentric muscle training. *Medicine and Science in Sports and Exercise*. 1976;8:35-38.

63. Mannheimer J. A comparison of strength gain between concentric and eccentric contractions. *Physical Therapy*. 1969;49:1201-1207.

64. Duncan P, Chandler J, Cavanaugh D, Johnson K, Buehler A. Mode and speed specificity of eccentric and concentric exercise training. *Journal of Orthopaedics and Sports Physical Therapy*. 1989;11:70-75.

65. Komi P, Buskirk E. Effect of eccentric and concentric muscle conditioning on tension and electrical activity in human muscle. *Ergonomics*. 1972;15:417-434.

66. Tomberlin J, Basford J, Schwen E, et al. Comparitive study of isokinetic eccentric and concentric quadriceps training. *Journal of Orthopaedics and Sport Physical Therapy*. 1991;14:31-36.

67. Higbie E, Cureton K, Warren G, Prior B. Effects of concentric and eccentric training on muscle strength, cross-sectional area, and neural activation. *Journal of Applied Physiology*. 1996;81:2173-2181.

68. Hortobagyi R, Hill J, Houmard J, Fraser D, Lambert N, Israel R. Adaptive responses to muscle lengthening and shortening in humans. *Journal of Applied Physiology*. 1996;80:765-772.