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The Relationship Between Intercondylar Notch Size and the Size of the Anterior Cruciate Ligament in Males and Females

by
KELLY KLASSEN

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THE RELATIONSHIP BETWEEN INTERCONDYLAR NOTCH SIZE AND THE SIZE OF THE ANTERIOR CRUCIATE LIGAMENT IN MALES AND FEMALES

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KELLY KLASSEN

A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University

of Manitoba in partial fulfillment of the requirements of the degree

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ABSTRACT

Anterior cruciate ligament (ACL) injuries are currently epidemic in females. A number of potential predisposing factors to ACL injuries have been reported including: smaller bone structure, a wider pelvis, a larger Q-angle, genu valgum and recurvatum of the knees, decreased muscle mass, strength, and endurance, and decreased overall fitness and poorer coaching in younger age groups.

It has also been suggested that the intercondylar notch of the femur plays a role in this predisposition toward ACL injury. This role is controversial. Radiographic examination has found that the shape of the notch varies with gender - a wider, reverse U shape in males, and a narrower, A shape in females. The theory is that during certain jumping or cutting moves, the narrow, A-shaped notch actually shears the ACL, or, that the small, narrow notch houses a congenitally smaller and therefore weaker ACL. The purposes of this study were to determine if there was an absolute difference between male and female measurements of both the intercondylar notch and the anterior cruciate ligament, to determine if there was a relationship between the size of the intercondylar notch and the size of the ACL, to determine if there was a predictive value of the size of anatomical structures, and to determine if there was a relationship between notch and ACL size, and height and body mass.

Thirty-four subjects (18 females and 16 males) were recruited for this study through poster advertising and word of mouth. Each subject had a magnetic resonance imaging (MRI) scan of their knee. The femoral intercondylar notch and the anterior cruciate ligament were imaged in the knee of each subject. The following measurements were made of the intercondylar notch on both axial and coronal view MR images: intercondylar notch width (at the level of the popliteal recess, at two-thirds notch height, and at the articular margins of the medial and lateral femoral condyles), notch height, notch angle, lateral wall angle, width of the femoral condyles (the greatest width, and the width at the level of the popliteal recess), and notch depth. Measurement was also made of the length, width, and angle of pull of the anterior cruciate ligament.

The data was analyzed using an analysis of variance (ANOVA) to determine if there were statistically significant differences between the size of the notch and the size of the ACL in males as compared to females, a stepwise multiple linear regression to determine if there was a predictability of the size of anatomical structures, and multiple correlations to determine if there was a relationship between the size of the notch and the size of the ACL and height and body mass.

From these analyses, the study found significant differences between males and females with regard to notch width at three levels, notch height, femoral bicondylar width at two levels, and notch depth on axial view MR images. Differences in notch height and notch depth disappeared when these measurements were repeated on coronal view MR images. No significant differences were found for notch angle or lateral wall angle on either the axial or coronal MR images.

The ACL was found to be significantly longer (absolute size) in males. No significant differences were found between males and females with regard to ACL width or angle of pull.

Notch and femoral condyle size was generally shown to be poorly related to ACL length and width when males and females were analyzed separately, but showed a significant correlation with ACL length when male and female results were combined. Notch angle and lateral wall angle showed a strongly correlated to the ACL angle of pull in males.

Intercondylar notch width was not correlated to ACL width but was found to be a negative predictor of ACL width. Axial intercondylar notch and femoral condyle measurements appeared to have many of the same predictive factors as coronal notch and femoral condyle measurements. The predictive factors for ACL length were the same, regardless of whether axial or coronal notch and femoral condyle measurements were used.

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There were many moments throughout this journey when I felt like giving up. This was a true test of my determination, commitment, and endurance. I could not have completed this thesis without the help and support of many.

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Thank you to my mom for doing "everything else" so I had every night to work, to Liane Bailey for always asking how things were going and for your encouragement, and to Jason Young for scanning "all those knees" for me.

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CHAPTER 1

INTRODUCTION

The participation of women in athletic endeavors or sports at all levels has increased dramatically in recent years (Huston and Wojtys, 1996). All over the world, there are women playing various sports including basketball, soccer, hockey, and volleyball from the high school to the professional and national level. According to the National Federation of State High School Associations and Department of Education Statistics (1998), one in three girls participated in high school sports in 1998, and women represented 40% of all high school and college athletic participants. In 2000-01, there were 3,921,069 boys and 2,784,154 girls participating in high school athletics. This greater participation has increased overall awareness of the medical and health issues related to the female athlete as increasing numbers of women are being seen with injuries in various medical facilities (Rochman, 1996; Beck and Wildermuth, 1985). In particular, an increased incidence of anterior cruciate ligament (ACL) tears has been noted in female athletes (Arendt and Dick, 1995). Between 1989 and 1993, the ACL tear rate in soccer has been reported to have been more than double for women than men. This rate increased to nearly triple between 1994 and 1998 (Arendt, Agel, Dick, 1999). In basketball, between 1989 and 1993, the ACL tear rate for women was reported to be more than four times that of the men's. Between 1994 and 1998, that rate remained high at nearly triple that of the men (Arendt, et al., 1999).

The reports from the athletes are similar, with the injuries often occurring in unlikely circumstances. An example is the soccer player who plants and cuts in attempt to avoid the attacking defensive player, and the basketball player who comes down from a rebound, landing with a straight leg, or tries the one-step stop (Arendt and Dick, 1995; Hutchinson and Ireland, 1995). Regardless of the mechanism of injury, the result is usually a season ending injury followed by reconstructive surgery and six to eight months of rehabilitation.

ACL injuries are currently epidemic in women's college athletics, especially in basketball, handball, and soccer (Arendt and Dick, 1995). Little research has been published, however, to explain the reason why female athletes are suffering this debilitating injury at such an increased frequency. Several possible explanations have been proposed, including such anatomical differences as increased Q-angle, their smaller bone structure, and decreased muscle mass in both absolute terms and relative to body mass (Janssen, Heymsfield, Wang, Ross, 2000), and physiological differences in strength, conditioning, playing experience, and skill level (Beck and Wildermuth, 1985).

It has also been suggested that the intercondylar notch of the femur plays a role in this predisposition toward injury (Shelbourne, Davis, Klootwyk, 1998; Muneta, Takakuda, Yamamoto, 1997; LaPrade and Burnett, 1994; Lund-Hanssen, Gannon, Engebretsen, Hoten, Anda, Vatten, 1994). The role of the intercondylar notch in contributing to ACL rupture is controversial. Prior to about 1994, it had received considerably less attention than some of the other proposed factors. Since then interest in the role of the notch has increased (Davis, Shelbourne, Klootwyk, 1999; Staeubli, Adam, Becker, Burgkart, 1999; Anderson, Dome, Gautam, Awh, Rennirt, 2001; Rizzo, Holler, Bassett, 2001). It has been theorized that the actual shape of the notch may vary with gender. Radiographic examination has found that males tend to have wider notches shaped like a reverse U, a sideways C, or an H, while females tend to have narrower notches shaped like an A (Hutchinson and Ireland, 1995). The theory is that during certain jumping and cutting moves, the narrow, A-shaped notch actually shears the ACL (Rochman, 1996). The other theory is that the small, narrow notch houses a congenitally smaller and therefore weaker ACL (Hutchinson and Ireland, 1995).

Statement of the Problem

It is important to examine whether there is a relationship between the intercondylar notch and the ACL. The purpose of this study will be to determine if there is a relationship between the configuration of the intercondylar notch (i.e. width, height, depth, etc.) and the size of the anterior cruciate ligament (i.e. length, width, etc.) in female subjects as compared to male subjects.

Hypotheses

There is a difference between male and female dimensions of both the ACL and the intercondylar notch, such that male values are larger than female values.

There is a positive relationship between the dimensions of the intercondylar notch and the size and angle of pull of the anterior cruciate ligament, so that a larger notch will be related to a larger ligament and a ligament that pulls at a more obtuse angle.

There is a predictive value of the size of anatomical structures. The size of the intercondylar notch, as well as the size of the ACL, can be predicted by certain predictive factors (notch width, notch height, notch angle, lateral wall angle, femoral bicondylar width, notch depth, ACL length, ACL width, ACL angle of pull).

There is a positive relationship between intercondylar notch size and ACL size and angle of pull to height and body mass, so that a larger notch and larger ACL will be related to increased height and increased body mass.

Definitions

Good health - the subject presently has no medical conditions that might make participation in an MRI study hazardous. These conditions include: heart conditions, claustrophobia, high blood pressure, metal implants of any kind, seizure disorders, pregnancy

Computed tomography (CT) - an imaging method which combines the use of a digital computer with a rotating x-ray device to create detailed images or “slices” of different organs and structures in the body

Magnetic resonance imaging (MRI) - an imaging method which uses a high-powered cylindrical magnet, without radiation, to produce detailed, three-dimensional images of the human body

Notch width index (NWI) - the ratio of the width of the intercondylar notch to the femoral bicondylar width

Anterior cruciate ligament (ACL) length - the longest fibres of the ACL as seen on an oblique sagittal MR image

Limitations and Delimitations

Limitations

1. There were limited number of existing protocols using MRI to measure the intercondylar notch. There were only two original research articles (Herzog, et al., 1994; Anderson, et al., 2001) that image the notch using MRI and subsequently used these images to measure various lengths, widths, angles, etc.

2. This study was limited by the limited number of studies available which described options as to how to obtain the best view of the anterior cruciate ligament. There were only two original research studies (Buckwalter and Pennes, 1990; Do-Dai, Stracener, Youngberg, 1994) that described a protocol for imaging the entire length of the ACL. There were several studies which used MRI to image the anterior cruciate ligament. However, the majority of these studies used only individual sagittal, coronal, or axial images, which do not enable visualization of the entire ACL.

3. The study was limited by the number of subjects. Thirty-four subjects were tested, 18 females and 16 males.

4. This study was limited by the subjects' self-report of their height and body mass.

Delimitations

1. There were only two original research articles available that used MRI to obtain images and measurements of the intercondylar notch (Herzog, et al., 1994; Anderson, et al., 2001). The protocol of Herzog, et al. (1994) was used for this study.

2. The age of the subjects. All subjects were between 17 and 30 years old.

3. The number of subjects. Thirty-four subjects were recruited for this study, 18 females and 16 males.

4. All subjects were in good health. No subject had any medical conditions that might have made participation in an MRI study hazardous. These conditions included: heart conditions, claustrophobia, high blood pressure, metal implants of any kind, seizure disorders, and pregnancy.

5. No subject had any previous injury to the anterior cruciate ligament, posterior cruciate ligament, medial collateral ligament, lateral collateral ligament, or either meniscus.

6. No subject had any previous knee surgery.

CHAPTER 2

REVIEW OF LITERATURE

Knee Injuries and the Female Athlete

There are reported differences in the types of knee injuries seen in females as compared to males. Females tend to present more often with patellofemoral pain and noncontact ligament sprains, while meniscal tears and direct contact ligament sprains are seen more often in males (Beck and Wildermuth, 1985). These patterns suggest differences in the female knee that may predispose it to specific injuries. These factors can be divided into intrinsic and extrinsic factors.

Intrinsic factors are anatomical differences. Due to overall smaller body size, females have smaller bones than males. The bones that make up the knee joint, the distal end of the femur, the tibia, and the patella are all smaller in women as compared to males of similar size.

Also noted is an increased number of limb malalignments in females. In particular, the wider pelvis of females creates a larger angle of pull of the quadriceps muscles (larger Q-angle) (Figure 1.) and a genu valgum (knock knees). Normally, the Q-angle is between 13 and 18 degrees, 13 degrees for males and 18 degrees for females (Magee, 1992). A Q-angle greater than 15 degrees for males and greater than 20 degrees for females are thought to be clinically abnormal (Shambaugh, Klein, Herbert, 1991). Both of these may cause increased stress on the medial and internal structures of the knee joint (Beck and Wildermuth, 1985; Shambaugh, et al., 1991).

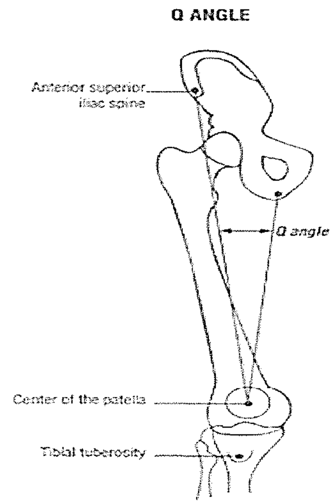


Fig 1. The static Q angle is determined by measuring the acute angle produced by the intersection of two lines. The first line is drawn through the anterior superior iliac spine and the midpoint of the patella. The second line is drawn through the midpoint of the patella and the tibial tubercle.

Figure 1. Measurement of the Q-angle (Huston, Greenfield, Wojtys, 2000).

Females also tend to have an increased recurvatum at the knee, implying a laxity in the posterior capsule (Hutchinson and Ireland, 1995) (Figure 2). This posture of hyperextension may produce a preloading effect on the ACL since it increases tension on the ligament, and any additional extension force may lead to failure of the ligament (Loudon, Jenkins, Loudon, 1996).

Figure 2. Genu Recurvatum of the Knee.
(internet - www.echo.uquam.ca/mednet/anglais/hermes_a/knee/part_1.html)

It has also been suggested that the intercondylar notch of the femur plays a role in the predisposition toward ACL injury (Shelbourne, et al., 1998; Muneta, et al., 1997; LaPrade and Burnett, 1994; Lund-Hanssen, et al., 1994). The role of the intercondylar notch in contributing to ACL injury is controversial. Prior to about 1994 it had received considerably less attention than some of the other proposed factors. Since then, interest in the role of the notch has increased (Davis, et al., 1999; Staeubli, et al., 1999; Anderson, et al., 2001; Rizzo, et al., 2001). It has been theorized that the actual shape and size of the notch may vary with gender. Radiographic examination has found that males tend to have wider notches shaped like a reverse U, a sideways C, or an H, while females tend to have narrower notches shaped like an A (Hutchinson and Ireland, 1995). The theory is that during certain jumping and cutting moves, the narrow, A-shaped notch actually shears the ACL (Rochman, 1996). The other theory is that the small, narrow notch houses a congenitally smaller and therefore weaker ACL (Hutchinson and Ireland, 1995).

Extrinsic factors include physiological differences, and differences in skill and conditioning or lack thereof. Several studies (Arendt, 1994; Hutchinson and Ireland, 1995; Powers, 1979; Rochman, 1996) have described the difference in muscle mass and strength between the sexes. By virtue of the difference in body size, females have less volume of muscle available. Powers (1979) initially described the female body as being 23% muscle while the male body is 40% muscle.

Similar results were reported by Miller, MacDougall, Tarnopolsky, and Sale in 1993 when they examined gender differences in strength and muscle fiber characteristics. Eight males and eight females were chosen as subjects. Subjects were matched for age, weight, and physical activity levels. Lean body mass was determined by subtracting fat mass from total body mass. Body density was determined by hydrostatic weighing, and percent body fat was calculated from body density. The strength of subjects was measured using a maximum voluntary isometric contraction (MVC) on a custom-made dynamometer and a one-repetition maximum (1RM) isotonic strength test on a Global Gym (Miller, et al., 1993). The investigators report that the males had significantly greater lean body mass ($P< 0.01$). The males were significantly stronger than the females in both upper and lower limb strength ($P< 0.01$). Absolute knee extension strength in the women was 62% and 69% that of the male 1RM and MVC respectively. Absolute upper body strength for the women was 52% that of the men for both 1RM and MVC (Miller, et al., 1993).

When strength was expressed relative to lean body mass, the males were still significantly stronger in both arm and leg strength, with the females being 70% and 80% as strong as the males in the arms and legs respectively (Miller, et al., 1993).

Janssen, et al. (2000) reported significantly ($p<0.001$) more skeletal muscle in men as compared to women in both absolute terms (33.0 versus 21.0 kg) and relative to body mass (38.4 versus 30.6%).

Huston, Greenfield, and Wojtys (2000) and Huston and Wojtys (1996) reported possible predisposing neuromuscular factors for ACL tears in females. They described how, when elite male and female athletes were compared to each other and to a nonathletic control group, significant differences were found in muscle strength and endurance, muscle recruitment preference, and time to generate peak muscle torque. Female athletes and controls demonstrated significantly less muscle strength and endurance than males ($p<0.05$). Increased muscle strength and endurance may mean increased support and stability for the knee. Decreased muscle strength means an increased dependency on ligaments for support. Compared to male athletes and female controls, female athletes tended to recruit their quadriceps muscles first for initial knee stabilization, while male athletes and female controls appeared to rely more on their hamstring muscles. This initial tendency toward quadriceps recruitment in female athletes increases the strain on the ACL during activity as the quadriceps muscle force tends to increase the anterior displacement of the tibia on the femur. Increased recruitment of the hamstrings would oppose this anterior displacement of the tibia and decrease the strain on the ACL. Female athletes also took significantly longer to produce hamstring peak torque (430msec) than male athletes (328msec) during isokinetic testing. Again, if the hamstrings are slower to respond during joint stabilization, there is increased anterior tibial translation due to the pull of the quadriceps muscles, and increased strain on the ACL. For these female athletes, a lower extremity muscle rebalancing and conditioning program may be key (Huston and Wojtys, 1996).

Several authors (Davis and Brewer, 1993; Huston and Wojtys, 1996) have noted that the blame for increased ACL tears falls on a decreased level of overall fitness and poorer coaching for females, especially in younger age groups (Beck and Wildermuth, 1985). The results are poor fundamental motor patterns, and inadequate skills, conditioning, and experience, which leaves the female collegiate athlete unprepared for the new higher level of competition and therefore vulnerable to injury (Beck and Wildermuth, 1985).

Rochman (1996) agreed with this analysis. She describes how women's training programs have improved but only at the elite level. She states that younger female athletes still often do not receive proper coaching and training to prepare them for collegiate competition, and that they need increased practice in executing skills safely. As a result, they do not get as strong as males and are not as fast in the important muscles, the hamstrings and calves (as described by Huston and Wojtys, 1996).

Anatomy of the Knee Joint

The knee is the largest and possibly the most complex joint in the human body. It allows rotation about two axes. It restrains rotation about a third axis and controls translation in all three planes. The knee bears loads that frequently exceed the body's weight by two to three times, and it's location between the body's two longest lever arms makes it especially prone to injury. Because it lacks bony stability, it depends upon a complex arrangement of ligaments, menisci, and musculotendinous units to maintain normal alignment and stability.

Bone Structure

The bones that make up the knee joint include the distal end of the femur, the proximal tibia, the fibula, and the patella. The femur (thigh bone) is the longest, strongest, and heaviest bone in the body. Its length is approximately one quarter of a person's height (approximately 18 inches). Its function is to transmit the body weight from the hip bone to the tibia when a person is standing (Moore, 1999). The femur consists of a head, neck, greater and lesser trochanters proximally, shaft, and medial and lateral condyles distally (Moore, 1999).

The shaft of the femur is smooth except for the linea aspera on the posterior aspect-a prominent, rough ridge with medial and lateral lips. This ridge provides an attachment site for portions of the quadriceps and adductor muscle groups and for the short head of the biceps femoris (Moore, 1999).

The distal end of the femur is broadened into two large condyles, medial and lateral, which articulate with the proximal surface of the tibia to form the knee joint. Anteriorly, the condyles merge into a shallow groove called the patellar groove for articulation with the patella. Each of the condyles has a projection called an epicondyle for muscle attachment. The condyles are oblong and project posteriorly, separated by a deep U-shaped intercondylar notch (Moore, 1999).

The tibia is the second largest bone of the skeleton. It's primary function is weightbearing. The proximal end is large with the superior surface flat and divided into medial and lateral tibial plateaus by the intercondylar eminence. The medial and lateral tibial plateaus provide articular surfaces for the large condyles of the femur. The intercondylar eminence serves as an area for ligamentous attachment. It does not articulate at any point with the gliding surface of either femoral condyle (Moore, 1999).

The fibula is the small, lateral bone of the lower leg. It has a narrow shaft and an irregularly shaped head which articulates with the inferior surface of the lateral tibial condyle. The fibula has little or no function in weightbearing, but rather serves as a site for muscle attachment and provides some added support for the tibia (Moore, 1999).

The patella is a small, triangular sesamoid bone which lies embedded within the quadriceps tendon. The primary function of the patella is to improve the efficiency of the quadriceps in extending the knee by holding the tendon away from the axis of rotation, thereby lengthening the lever arm of the quadriceps muscle force. With a longer lever arm, the quadriceps muscles need to produce less force to maintain the amount of torque around the knee joint (Nordin and Frankel, 1989). The patella also guides the quadriceps tendon, decreases friction between the quadriceps muscle and the bony surface of the femur, and provides a bony shield for the cartilage of the femoral condyles (Magee, 1992).

Ligamentous Support

The ligaments of the knee are its primary stabilizers and guide the movement of the bones in proper relation to one another. The medial collateral ligament is a strong, flat band, approximately 9 cm long. It attaches to the medial femoral condyle superiorly and to the medial superior surface of the tibia distally. This ligament is made up of two layers, one superficial and one deep. The deep layer is a thickening of the joint capsule and blends with the medial meniscus. The superficial layer is a strong strap which blends with the posterior capsule (Moore, 1999).

A portion of the medial collateral ligament is taut throughout the entire range of knee joint motion. All of the fibres are tight in full extension. In full flexion, the anterior fibres are the most taut; in midrange, the posterior fibres are the most taut (Magee, 1992).

The lateral collateral ligament is a round cord about 5cm long which attaches to the lateral femoral condyle superiorly and runs inferiorly to attach to the head of the fibula. This ligament lies anterior to the tendon of the biceps femoris muscle. It is not attached to the lateral meniscus nor is it part of the joint capsule. The primary function of the lateral collateral ligament is to restrain lateral movement of the knee (Magee, 1992).

The Cruciate Ligaments

The cruciate ligaments are located between the medial and lateral femoral condyles. These strong ligaments are within the joint capsule but outside the synovial cavity. They cross each other obliquely in the shape of an "X" and are named anterior and posterior according to their tibial attachment. These ligaments are the primary rotary stabilizers of the knee (Magee, 1992).

Structure of the Anterior Cruciate Ligament

The anterior cruciate ligament is the weaker of the two intra-articular ligaments of the knee (Figure 3). It arises from a depression on the anterior part of the intercondylar area of the tibia, just posterior to the attachment of the medial meniscus. It extends superiorly, posteriorly, and laterally to a broad attachment on the posterior part of the medial side of the lateral condyle of the femur (Moore, 1999). The length and width of the ACL are variable. The mean length has been reported to range from 26.9mm to 32.5mm (Noyes and Grood, 1976; Butler, Guan, Kay, Cummings, Feder, and Levy, 1992). The width has been reported to range from 3mm to 10mm (Davis, Shelbourne, and Klootwyk, 1999). The function of the ACL is to resist anterior displacement of the tibia on the femur and to prevent hyperextension of the knee joint (Moore, 1999).

The possibility of there being actual anatomic divisions within the ACL is controversial, varying from none to as many as three distinct fascicular bundles. Both Dye and Cannon (1988) and Kwan (1993) have described a functional arrangement of fascicles into what has been termed the anteromedial bundle and somewhat larger posterolateral bundle. With a range of motion from full extension to flexion, the ACL twists on itself, which produces these functional components. The fascicles in the anteromedial bundle are thought to be the longest in flexion. These fascicles may be the primary component that resists anterior displacement of the tibia in flexion. The posterolateral fibres are described as being the longest in extension, and are the primary component that resists hyperextension.

The ACL is a highly vascularized structure. The predominant source of blood supply is the middle geniculate artery which branches off the popliteal artery and directly pierces the joint capsule. Smaller terminal branches of the lateral and medial inferior genicular arteries also contribute vessels to the synovial plexus through the connection with the infrapatellar fat pad. The periligamentous vessels send branches transversely into the substance of the ACL, which anastomose with endoligamentous vessels that lie parallel to the collagen bundles in the ligament (Dye and Cannon, 1988).

In addition to the well-developed blood supply, the ACL also has a nerve supply. Research has demonstrated neural elements on the periphery and within the ACL, which have been interpreted as mechanoreceptors similar to Golgi tendon organs. These neural elements generate the proprioceptive information that feeds into a complex myoneural network. This proprioceptive information could serve as the afferent limb of a reflex arc to protect the joint from damaging deformations (Dye and Cannon, 1988).

Mechanisms of ACL Injury

Recent reviews have described two mechanisms of ACL ruptures within the sports setting- through direct contact or through non-contact. Delfico and Garrett (1998) described direct contact injuries as most often the result of an excessive valgus force being applied to the knee. They describe a soccer player striking the lateral aspect of an opponent's knee during a slide-tackle, applying the valgus force.

Several reviews (Delfico and Garrett, 1998; Feagin and Lambert, 1985; Huston, Greenfield, and Wojtys, 2000; Kirkendall and Garrett, 2000) have reported the more common non-contact mechanism of ACL injury. Huston, Greenfield, and Wojtys (2000) state that a high percentage of these injuries occur when an athlete lands from a jump. There is a sudden deceleration and an abrupt change of direction with the foot in a fixed position (Feagin and Lambert, 1985; Delfico and Garrett, 1998). Delfico and Garrett (1998) report retrospective studies and videotape analysis which consistently revealed the knee in a position of between 30 degrees of flexion and full extension at the time of injury.

In trying to further define the exact mechanism of injury in non-contact ACL tears, Delfico and Garrett (1998) report multiple studies which propose that the force producing the tear is the result of an eccentric contraction of the quadriceps muscles. They describe that during the eccentric contraction, the quadriceps produce an anterior displacement force on the tibia, and that this force is greatest when the knee is between 30 degrees of flexion and full extension. They also note that the angle between the tibial shaft and the patellar tendon is greatest at 30 degrees of knee flexion. Therefore, they state that if force vectors were drawn, the anteriorly directed component exerted by the quadriceps on the tibia is greatest at 30 degrees of knee flexion, indicating that with an eccentric contraction and the knee in this position, the anteriorly directed force is potentially enough to cause injury.

An undated study by Boden, Dean, and Feagin described by Delfico and Garrett (1998) also found that when reviewing non-contact ACL tears, these injuries consistently tended to occur at or near footstrike with the knee at an average flexion angle of 21 degrees. The investigators report that at footstrike, there is a deceleration and an eccentric contraction in the quadriceps which produces the maximum force within the muscle. They state that this is known because, unlike concentric contractions, eccentric muscle contractions generate higher forces, and produce higher forces at higher velocities.

Arnheim (1999) describes another, although less common mechanism of ACL tears. With the knee in full extension, all fibres of the ACL appear to be in tension (Moore, 1999; Girgis, et al., 1975). Adding a hyperextension force from the front of the knee with the foot planted and it is easy to imagine structural failure of the ligament (Arnheim, 1999).

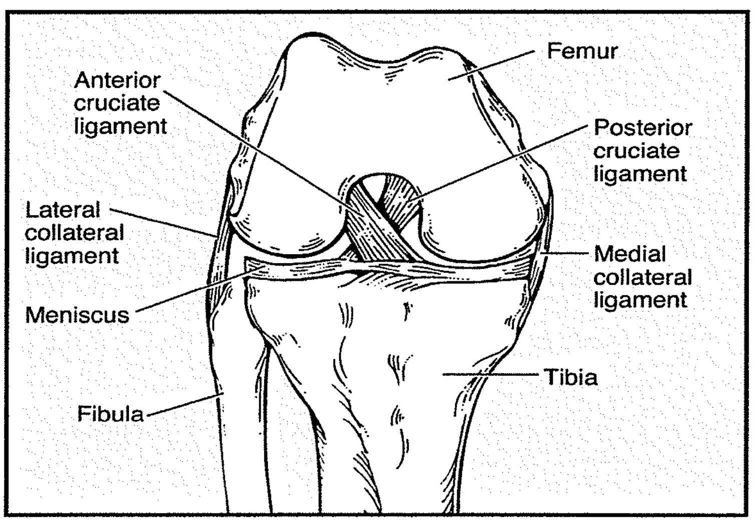


Figure 3. Location of the Anterior Cruciate Ligament (Levin, 1992).

Size of the Femoral Intercondylar Notch

The intercondylar notch is located at the distal end of the femur (Figure 4). The inferior aspect of this long thigh bone is marked by the prominent medial and lateral condyles. They project both posteriorly and inferiorly, leaving a deep notch, the intercondylar notch between them.

In order to determine what a narrow notch is, a value for a "normal" or "average" notch had to be established. Early studies attempted to address this question. In 1991, Good, Odensten, and Gillquist used six dissected specimens with intact ACLs to establish their "normal" values. The sizes of the intercondylar notch and femoral condyle width were made at multiple locations using a caliper and micrometer. They found their "normal" knees to have a mean notch width of 23.2 mm or a mean notch width index of .292. Notch width index is defined as "the ratio of the width of the intercondylar notch to the width of the distal femur at the level of the popliteal groove on a tunnel view radiograph" (Souryal, Moore, and Evans, 1988). According to Souryal, et al. (1988), this ratio eliminates magnification variability and differences in patient size.

The intercondylar notch width was then examined in three groups of subjects in order to establish normal values for notch width in uninjured subjects, subjects with a chronic instability from a previous ACL tear, and subjects who had an acute repair of a torn ACL. Group one consisted of 93 patients with a chronic instability. Group two consisted of 62 patients who had an acute repair of a torn ACL. Group three was a control group of 38 young adults without knee injuries. In all three groups, the knee was flexed to 90 degrees, and the intercondylar notch width was measured with a caliper just above the meniscal plane where the maximum width of the anterior opening of the notch is found. The mean notch width for group one was 16.1 mm, 18.1 mm for group two, and 20.4 mm for group three. The notch width index was not calculated for any of the study groups. However, based on the investigators previously calculated values for the "average" sized notch, all of the three study groups would have clinical notch stenosis, based on the notch widths all being less than 23.2 mm.

Anderson, Lipscomb, Liudahl, and Addlestone (1987) also attempted to determine an average notch size. They used a larger group of subjects. They used forty-eight subjects or ninety-six knees. Notch dimensions were computer generated from computed tomography scans. The mean NWI was .249, a slightly smaller value than that found by Good, et al. (1991).

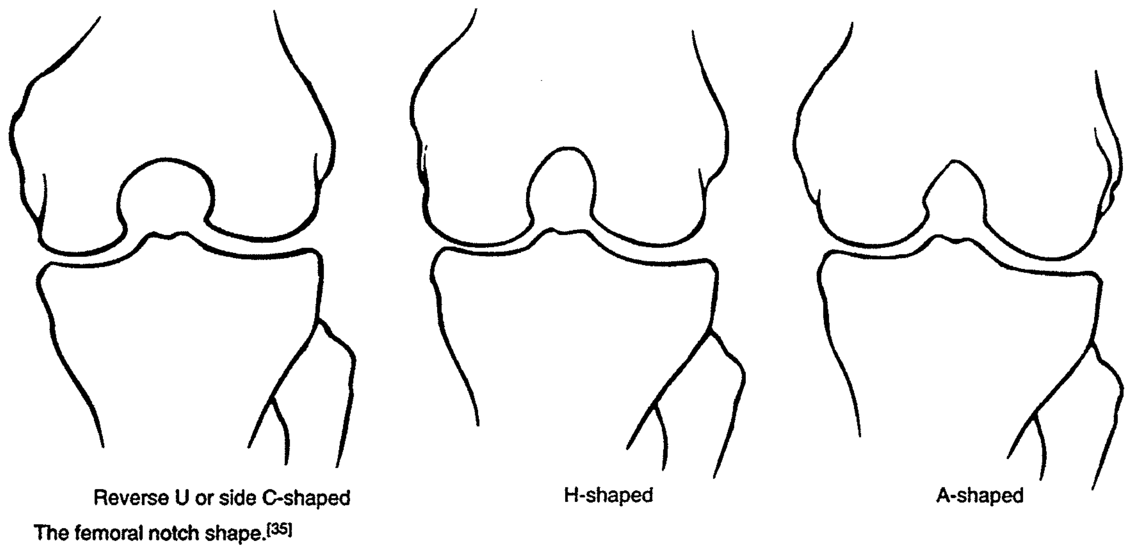


Figure 4. The Femoral Intercondylar Notch Shape (Hutchinson and Ireland, 1995).

Notch Size and ACL Injuries

Following the establishment of approximate values for the size of the intercondylar notch in a "normal" or uninjured population, the next question naturally became that of the size of the notch in those who had sustained ACL injuries. There is a consensus in the literature that there is a statistically significant relationship between notch stenosis (narrowing) and ACL tears despite the fact that all of the studies examined entirely different populations (Souryal and Freeman, 1993; Lund-Hanssen, Gannon, Engebretsen, Holen, Anda, and Vatten, 1994; LaPrade and Burnett, 1994; Houseworth, Vincent, Mauro, Mellon, Kieffer, 1987).

Souryal and Freeman (1993) chose to prospectively study high school athletes. Data from nine-hundred and two athletes from all sports was entered into the computer. Initial data included knee range of motion, thigh girth, and intercondylar notch width. Seven-hundred and eighty-three athletes were available for study two years later. There were 23 confirmed ACL tears in this group. Notch width measurements and ligament examinations were available on 20 of these athletes, 12 men and 8 women. The overall average NWI was 0.231. When males were compared to females, the males had a wider average notch, at 0.239, whereas the females had an average value of 0.217. This difference was statistically significant. Athletes who had sustained noncontact ACL injuries had significantly narrower notches than those who had sustained contact injuries when same sex comparisons were made. Women with noncontact injuries had a NWI of 0.165 ($p < 0.001$, compared to other women). Men with noncontact injuries had a NWI of 0.214 ($p < 0.001$, compared to other men). No male-female comparison was made between those with noncontact injuries or between those with contact injuries.

Lund-Hanssen, Gannon, Engebretsen, Holen, Anda, and Vatten (1994) followed the work of Souryal and Freeman (1993) with their study in 1994. Their subjects consisted of forty-six female handball players, twenty controls (uninjured) and twenty who had already sustained ACL tears. All players were of comparable height and weight. Again, using NWI to compare notch width, the uninjured subjects had an average NWI of .243 for the uninjured athletes, while the injured subjects had a significantly smaller value of .224.

LaPrade and Burnett (1994) chose to examine varsity intercollegiate athletes. Their study was similar to that of Souryal and Freeman (1993) in that they prospectively followed 213 athletes from various sports for two years. Once again, the NWI was used to compare notch size. The results revealed an average NWI of .243 and an average NWI of .193 for those athletes that were injured.

In 1987, Houseworth, Vincent, Mauro, Mellon, and Kieffer conducted a study on military cadets at West Point Academy in New York. They chose fifty subjects with acute ACL tears and fifty "normal" subjects with no history of knee injuries. Subjects were male and female ranging from eighteen to twenty five years of age. Plain radiograph films were used to image all of the knees. The area of the notch, however, was determined using computer graphics. The results did reveal that the area of the notch in those cadets who had sustained an ACL injury was smaller than those that were uninjured. The one difference was that apparently it was a stenotic posterior arch of the notch that placed a knee at risk for an ACL tear. The posterior arch is the narrowest part of the notch, according to Kieffer and Curnow (1984). In full knee extension, the anteromedial and intermediate bundles of the ACL lie tight against the intercondylar shelf. This study suggests that it is the anteromedial and intermediate bundles of the ACL that are torn in a strictly hyperextension injury. When an external rotational force is applied, the posterior arch of the notch may actually shear the ACL. This theory has not been confirmed by other studies.

Shelbourne, Facibene, and Hunt (1997) chose to study patients from their young adult population. The control group consisted of 100 males and 100 females. The study group consisted of 90 males with bilateral and 297 with unilateral ACL reconstructions, 41 females with bilateral and 129 with unilateral ACL reconstructions. The purpose of the study was to compare intercondylar notch width radiographically and intraoperatively to determine if there was a difference between uninjured patients and patients with unilateral and bilateral ACL tears. For the female group, the results revealed a mean notch width of 12.8mm in the bilateral group, 13.8mm in the unilateral group, and 14.5mm in the uninjured group ($P<0.05$). For the male group, the mean notch width was 15.3mm in the bilateral group, 15.8mm in the unilateral group, and 16.9mm in the uninjured group ($P<0.05$). The study concluded that the intercondylar notch width is narrower in females than males, and for both males and females, the notch width is narrower in patients with ACL injuries compared with uninjured patients.

Lastly, in 2001, Ireland, Ballantyne, Little, and McClay conducted a study of 294 subjects, 108 with ACL injuries (53 males, 55 females), and 186 uninjured (92 males, 94 females). The purpose was to not only determine if there was a relationship between the size of the notch and ACL injuries, but also to determine if there was a relationship between the shape of the notch and ACL injuries. Using radiographs, measurements were made of notch width and femur width. The notch width index was also calculated. The notch was also categorized as either A-shaped or non-A-shaped. The final analysis revealed that ACL-injured patients had significantly smaller notch widths and significantly smaller notch width indexes when compared to uninjured patients. The results also showed that notch shape was not related to injury status. A-shaped notches were smaller than non-A-shaped notches regardless of injury status or gender.

There are two studies that have found a non-significant relationship between notch size and ACL injuries. In 1997, Teitz, Lind, and Sacks examined eighty subjects, forty male and forty female. Using the existing radiographs, the investigators measured notch width and the femoral condyle width of both knees for all patients, and calculated the notch width index (NWI). The goals of the study were to determine if a significant difference existed between the NWI in the right and left knees of the same person, to determine if symmetry existed between the right and left NWI regardless of sex, and to see whether there was a difference in NWI as a function of sex or ACL injury. Paired t-tests were used to compare NWIs in the right and left knees in the same subject. Independent t-tests were used to compare the mean NWI in males and females, and to compare the mean NWI in subjects with ACL injuries and those with other diagnoses (i.e. torn meniscus, torn PCL, patellofemoral pain). Multiple regression analysis was performed to determine the effects of sex, age and ACL status combined on NWI. The study found that the NWI of the right and left knees in the same subject is symmetrical, regardless of sex or whether the subject was injured or uninjured. The overall mean NWI for injured subjects was 0.248 and 0.253 for uninjured (non-significant). The mean NWI for male injured subjects was 0.252 and for uninjured was 0.263 (non-significant). The mean NWI for female injured subjects was 0.244 and 0.243 for uninjured (non-significant). When male and female comparisons were made, the mean NWI for male, injured subjects was 0.252 and for female, injured subjects, was 0.244. In comparing uninjured subjects, the mean NWI for males was 0.263 and 0.243 for females. There was no significant difference found in either of the two comparisons.

The investigators concluded that NWI alone is not the critical factor in the patient with a unilateral, non-contact ACL tear, whether the subject is male or female. They also state that the increased incidence of ACL tears in females as compared to males cannot be attributed to NWI alone.

Also in 1997, Muneta, Takakuda, and Yamamoto used sixteen cadaver knees, eight male and eight female, to test their hypotheses that, one, the dimensions of the anterior cruciate ligament can be predicted by the intercondylar notch width, and two, that the size of the anterior cruciate ligament can be predicted by caliper measurement of the intercondylar notch.

The knee joints were dissected, leaving only the femur, ACL, and tibia with both menisci. The widths of the intercondylar notch and femoral condyles were measured directly with a caliper. A positive mold of the entire ACL, including the femoral and tibial insertions, was then created using silicone rubber and plaster commonly used for dental molding. The following measurements were then made: 1) femoral bicondylar width, 2) intercondylar notch width, 3) NWI, 4) sagittal length of the ACL. Each parameter was compared between males and females, and then their relationship to NWI was investigated. No significant difference was found between males and females in terms of notch width, NWI, and ACL width. ACL length was significantly greater in males.

The study concludes both narrow and wide notches contain ACL's of the same size, or, that a narrow notch does not contain a smaller, weaker ACL. The investigators suggest that the more likely mechanism of injury is that a normal-sized ligament is contained in a small, stenotic notch, and rotational and translational movements of the tibia on the femur may bind or impinge the ACL on the margins of the notch.

Notch Size and ACL Size

Following the cadaver study of Muneta, et al. (1997), there were several studies which attempted to answer the question of whether notch size was related to the size of the ACL.

In 1999, Davis, Shelbourne, and Klootwyk, examined the intercondylar notch width and its relationship to the width of the anterior and posterior cruciate ligaments using magnetic resonance imaging (MRI). Another purpose of the study was to test for male-female differences between notch and ligament measurements. The subjects were 57 females and 67 males with a mean age of 36.6. All subjects had an MRI scan of one of their knees which produced coronal images, each one being 3mm thick. The cut chosen for analysis was the one in which the ACL and PCL cross each other, as close as possible to the midsubstance of the ACL. Measurements were made of the femoral bicondylar width, notch width, ACL width, and PCL width. The mean bicondylar width for females was 68.7mm and the mean for males was 78.7mm. In females, the mean notch width was 16.2mm and for males was 19.0mm. This was a statistically significant difference. The mean ACL width for females was 5.7mm, and for males was 7.1mm. This was also a statistically significant difference. Using the Pearson correlation coefficient, a significant correlation ($r = 0.87$) was found between notch width and ACL width. This was also found to be statistically significant for both males ($r = 0.84$) and for females ($r = 0.80$). The conclusion of the study was that patients with narrow intercondylar notches have narrower anterior cruciate ligaments.

In 2001, Rizzo, Holler, and Bassett also examined ACL width and intercondylar notch width. Using cadaver specimens, the investigators measured ligament width and notch width in the knees of 15 males and 11 females. The ratio of ACL width to notch width was also calculated. Data regarding gender and age was also recorded. The mean age of the male specimens was 63.9 years, and was 69.9 for the female specimens. The results revealed the mean ACL width was 10.59mm for males and 8.09mm for females. This difference was statistically significant ($P<0.01$). The mean notch width for males was 20.18mm and 20.50mm for females. This difference was not statistically significant. A significant difference between males and females was also found for the ACL: notch width ratio.

Finally, in 2001, Anderson, Dome, Gautam, Awh, and Rennirt conducted a study to correlate anthropometric measurements, strength, ACL size, and intercondylar notch characteristics to sex differences in ACL tear rates. One hundred high school varsity basketball players, 50 boys and 50 girls with no previous knee injuries were recruited as study subjects. The average age for the males was 16.1 years and 16.2 years for the females. Measurements were made of height, weight, and percent body fat for each subject. Concentric muscle strength and endurance were also measured for the quadriceps and hamstrings at 60 and 240 degrees/second for each subject.

Each subject then had a magnetic resonance imaging (MRI) scan of both knees which produced sagittal oblique images of the ACL and axial images of the ACL and of the intercondylar notch. Measurements were made of the ACL in its anteroposterior dimension and of its width. The approximate area of the ACL was also calculated. Notch measurements included bicondylar width, lateral condylar width, notch width, and notch width at two-thirds the notch height. The notch width index was also calculated.

The analysis of strength found that the hamstring muscles in females were relatively weaker than in males when compared to the quadriceps muscles. This difference became even more significant ($P<0.01$) when adjustment was made for body weight.

Analysis of the MRI measurements found that all of the notch measurements (bicondylar width, lateral condylar width, notch width, and notch width at two-thirds notch height) were all significantly greater in males than in females. However, there was no significant difference in NWI for either the males or the females. The area of the ACL was significantly greater in males than in females. When corrected for body size, however, there was no significant difference in area. Correlation of ACL area to notch width was not significant for either males or females, but there was a significant correlation between ACL area and notch width at two-thirds notch height for females. There was also a correlation between ACL area and peak torque extension and total work extension.

The conclusions from the study are that: subjects who have stronger quadriceps have larger ACLs; as height increases, the size of the notch increases for males; as height increases, total condylar width increases for both males and females; as height increases, the size of the ACL increases for males. Generally, the study concludes that the size of the ACL does not vary in proportion to the size of the notch, and that it is a normal-sized ACL mismatched with a stenotic notch which predisposes it to injury.

Techniques of Measurement of the Intercondylar Notch

Not only is there ongoing debate over the role of the intercondylar notch in ACL injuries, there are varying opinions regarding the best way to obtain accurate measurements of notch dimensions.

The most widely used method is the radiograph, or the x-ray. They are used most often because they are easy to administer and are relatively inexpensive. However, radiographs may or may not give reliable measurements of notch dimensions. Three comparable groups of patients with bilateral, unilateral, and no ACL injuries were compared by Schickendantz and Weiker (1993). Absolute measurements were made on radiograph of notch width, notch height, condyle width, and condyle height. From the absolute measurements, eight mathematical ratios were calculated, including the notch width to the total width of the distal femur (i.e. the notch width index). Statistical analysis found no significant differences in any of the eight mathematical ratios between comparable groups of patients with bilateral ACL injuries, unilateral ACL injuries, and no ACL injuries. Schickendantz and Weiker (1993) interpreted this to mean that measurements of the notch as seen on radiographs may not be reliable or reproducible predictors of clinically significant notch stenosis as described by Anderson, et al. (1987) and Souryal, et al. (1988).

Souryal and Freeman (1993) disagreed with Schickendantz and Weiker (1993). They developed a frequency distribution of the notch width index for their study of 902 athletes. The distribution fell into the shape of a "normal" curve. They concluded that the measurements of condyle and notch width on plain x-ray could be accurately repeated often enough to confidently state that the NWI could be used for comparison in a large population. The NWI cannot, however, provide details on notch configuration. The authors caution that NWI should only be used as a screening tool to give a relative idea of notch size.

In 1998, Shelbourne, Davis, and Klootwyk examined the idea of the NWI further. They state that this ratio has been used in many studies because it standardizes differences in patient size. They further state that the ratio "assumes that both the notch width and femoral bicondylar width increase with increasing height, and therefore the ratio should be a valid means of standardizing for patient size".

However, it is the size difference between patients that is believed to be important, specifically with regard to the absolute notch width. The NWI does not take into account these anthropometric differences between males and females. Shelbourne, et al. (1998) found that notch width does not directly increase with increased height for both sexes. They concluded that the NWI is not effective for standardizing people of different heights since the ratio assumes that notch width and femoral bicondylar width directly correlate. These authors suggest that measuring the absolute notch width is more useful than using the NWI measurement.

In addition to the issue of the reliability of radiographs, there is also disagreement as to the best position in which to place the subject in order to obtain the optimal view of the notch on film. Standing radiographs were used by Schickendantz and Weiker (1993). This is the same study that suggested that radiographs might not be reliable. No rationale is provided as to why the standing position was chosen or if there are any other studies that advocate this view. An x-ray taken with the subject standing may produce an image with an incomplete view of the notch. If the subject had a very lax posterior capsule (hyperextending knees) or had a large genu valgum or varum, the femur may sit slightly rotated on the tibia and the view would not be completely anterior-posterior, so some of the area of the notch might not be seen.

Both Souryal and Freeman (1993) and Lund-Hanssen, et al. (1994) positioned their subjects on their hands and knees, knees on the film, the tibia parallel to the table, with 70 degrees of flexion in the knee. The x-ray beam was perpendicular to the film. Again there is no explanation for this position except that it gives a view of the intercondylar notch. These are the first two studies in which an attempt to standardize procedures has been made.

LaPrade and Burnett (1994) also had their subjects prone on hands and knees, kneeling on the film. Their only modification was to have the subjects knees flexed to 45 degrees instead of 70 degrees. This angle was formed between two lines: the first from the centre of the lateral malleolus to the centre of the knee joint, and the second, from the centre of the knee joint to the centre of the hip joint. Their argument was that any amount of abduction or adduction of the femur "caused distortion of the outlines of the intercondylar notch". Placing the knee in 45 degrees of flexion puts it in a "neutral" position, therefore eliminating the abduction and adduction and the distortion. From this one study it appears that 45 degrees of knee flexion is an effective position, but further radiographic study is required in order to validate this finding.

Magnetic Resonance Imaging and Computed Tomography

Magnetic resonance imaging and computed tomography scans are increasingly becoming the technology of choice when it comes to obtaining accurate intercondylar notch measurements.

Computed Tomography

Computed tomography is an x-ray imaging method that produces images of selected slices or planes through the body. In conventional x-ray imaging, the image is formed by projecting a large x-ray beam through the body and casting shadows of internal body structures. In CT, two steps are required to form an image. The first step consists of passing an x-ray beam through the edges of the slice while the beam is rotated around the body. The amount of radiation that penetrates the body section is measured and the data is stored in the computer memory. In the second step, the computer reconstructs and creates the image (Gedgaudas-McClees and Torres, 1990).

During the scanning session, the x-ray beam is rotated around the patient's body. Normally, one scan operation consists of one complete 360 degree rotation. The scan is produced by rotating the x-ray tube around the body. The speed of rotation and total time required is adjustable and is set by the operator. Generally, one scan ranges from 1 to 15 seconds (Gedgaudas-McClees and Torres, 1990).

One scan is required for each image. Since a normal CT examination consists of a set of images, the process must be repeated for each slice location. The CT system is programmed prior to the examination to move the patient into the correct position for each scan (Gedgaudas-McClees and Torres, 1990).

Computer tomography has three main advantages over traditional x-rays. First is the ability to image virtually any structure or tissue in detail due to its high contrast resolution. Second, with the ability to produce images in slices, any tissue can be viewed at any precise location. Third, is its accessibility. Normally, the time between an appointment booking and the actual scan date is four to six weeks in Manitoba. This is not nearly as fast as an x-ray, but the wait for a magnetic resonance imaging (MRI) scan may be months.

Despite its advantages, there are some limitations to CT scanning. As stated above, the wait for the actual scan can take weeks and the cost of the scans can be expensive depending on the number of images to be made. There is also potentially harmful radiation exposed to the body with each scan.

Anderson, et al. (1987) analyzed forty-eight subjects (96 knees) using a computed tomography (CT) scanner to illustrate the accuracy of this technology. The computer was programmed to make three cuts and to take several measurements at each cut. At cut one, the following measurements were made: the notch opening angle (the angle between the lines connecting the apex of the notch and the articular margins of the femoral condyles), notch height (the distance from the apex of the notch to a line connecting the articular margins of the femoral condyles), notch width (the maximum distance between the articular margins of the femoral condyles), condyle width (the maximum mediolateral distance), notch area (notch width multiplied by the notch height), and condyle area (the total area of the condyles including the space occupied by the notch less the area of the notch as previously calculated). On cuts two and three, the area of the notch, area of the condyle, and length of the intercondylar shelf (could be likened to the roof of the notch) were calculated. The angle of the femoral shaft and intercondylar shelf were also drawn by the computer. All of the scans were performed by the same technician, and all measurements except the angle of the femoral shaft were computer generated from tracings of landmarks to reduce measurement variability. Reliability of the measurements was not reported.

The use of the computer minimizes errors that can be attributed to the technician. It also eliminates variability with regard to subject position, angle of the knee, projection, and magnification which are often encountered when using plain films.

Magnetic Resonance Imaging

Magnetic resonance imaging has evolved into a very accurate method of examining both normal and pathological soft tissue anatomy. MRI is often selected for its ability to simultaneously image hard and soft tissues and show a joint in cross-sectional slices. There is no potentially hazardous radiation, and it is non-invasive so the knees of living persons can be imaged as opposed to specimens (Friedman and Jackson, 1996). Its multiplanar imaging capabilities and excellent soft tissue contrast allow virtually any tissue or structure to be viewed in clear detail.

MRI was first introduced for imaging the knee by Reicher, Rauschning, Goid, Bassett, Lufkin, and Glen (1985). Since then its popularity has increased dramatically as an imaging modality of the knee. In the past ten years alone, it has become the most common imaging technique of the knee (Friedman and Jackson, 1996). The MR signal arises because water (in tissues or elsewhere) can become slightly magnetized when put into a magnetic field. The magnetization is weak enough that it doesn't affect any chemical or physiological processes so the subject does not feel it. The source of the magnetization is the hydrogen nuclei (protons) in the water because these nuclei have a magnetic moment, or a north and a south pole and a magnetic field around them like a bar magnet. In a magnetic field they tend to line up with the field making a "net magnetization". Thermal motions tend to disrupt this alignment so there is never total alignment (Stoller, 1997).

Magnetization, like any magnetic field has a magnitude and direction. The magnetization in the water is aligned with the magnetic field of the MR system when everything is in equilibrium. When a pulse of a magnetic field oscillating at a specific frequency (an electrical current) is applied through the MR coil, the magnetization is tipped away from alignment with the magnetic field of the MR system (Stoller, 1997).

When the magnetization is not aligned with the system magnetic field, the forces on it tend to push it back towards alignment, which is the equilibrium state and the lowest energy state of the system. It does not simply snap back to alignment, however. The system has to lose the energy that was put into it. This process is called “relaxation”, as the system returns toward equilibrium. Relaxation can be described in terms of two time constants. T1 describes the recovery time of the magnetization parallel to the static field, and T2 describes the decay of the transverse magnetization (Stoller, 1997).

Only the magnetization transverse to the static magnetic field can be detected. This is because while the magnetization is trying to recover to equilibrium, the forces on it make it rotate (precess) around the direction of the static magnetic field. The rotating magnetization in the water that results induces a current in the MR coil. This is what is recorded as the MR signal.

The images produced by MR imaging appear similar to those produced by x-ray film and are read in a similar fashion. The difference is that while plain film only allows viewing of bony structure, an MR film enables virtually any structure to be seen. This is accomplished through the use of various sequences using different repetition times, echo times, pulse sequences, and slice thicknesses. All of these variables can be manipulated in order to accentuate the contrast and provide the best resolution of the desired structure (Friedman and Jackson, 1996). MR imaging also enables three-dimensional viewing of structures at any precise location, simply by selecting the desired slice.

Despite its increasing popularity, there are some limitations to MR imaging. The high cost of the procedure is the most significant deterrent. Included in this is the cost for technicians, the equipment itself, and the cost of imaging time. Another limitation of its use is in patients with significant claustrophobia. There is also the question of availability. MR scanners are few in number and the time between an appointment booking and the actual date of imaging can be months.

MRI was validated to measure the intercondylar notch by Herzog, et al. (1994). Ten cadaver knees were used for the study. The following measurements and calculations were made: intercondylar notch width, height and angle, lateral wall angle, mediolateral dimension of the femoral condyles, width of the femoral condyles at the popliteal recess, height of the patella, the anterior-posterior dimension of the proximal tibia, and calculation of the NWI. All measurements were made on each cadaver knee using MRI and plain film radiographs. Direct measurements were also made with calipers. In order to determine if there were any significant differences between the groups, correlation coefficients were calculated.

The x-ray measurements were significantly different (greater) than the direct cadaver measurements. The MRI measurements were not significantly different from the cadaver measurements, meaning that the MRI measurements were accurate in obtaining the actual notch dimensions. According to Herzog, et al. (1994), the problem with plain film is that it is a two-dimensional representation of the three-dimensional knee, and the exact location of straight lines drawn on the curved bony surfaces can be difficult to determine.

Radiographs are still the most used method of determining dimensions of the intercondylar notch. The results, however, appear to be limited due to the possible inconsistent reproducing of images, and the inability to precisely locate a specific point on a two-dimensional image. The result may be unreliable measurements. They are, however, still useful in detecting abnormalities. Radiographs may be used as a screening tool to determine the general size of the intercondylar notch. Researchers must realize that "the range of error of radiographs is greater and the exact location of measurement is not as precise as obtained on cross-sectional and multiplanar studies" (Herzog, et al., 1994), such as MRI and CT scans.

MR Imaging Techniques of the Anterior Cruciate Ligament

Early studies related to the application of MRI have shown that the anterior cruciate ligament can be imaged successfully. The ACL can be imaged in four planes- sagittal, coronal, axial, and oblique sagittal. Most of the research related to MR imaging of the ACL involves the diagnosis of tears. Sagittal images are the most common in this regard. They are the most effective for depicting the continuity of the ligament (Reicher, et al., 1985). However, the ACL follows a complex course as it runs superiorly and laterally from the tibia to its attachment on the femur, winding and twisting on itself. This can create difficulty in viewing the entire ligament on a straight sagittal image. Fitzgerald, Remer, Friedman, Rogers, Hendrix, and Schafer (1993) describe this incomplete visualization, especially of the midportion and of the proximal and distal attachments.

Coronal and axial images are excellent compliments to the sagittal images, especially if portions of the ligament are obscured on the sagittal views (Friedman and Jackson, 1996). Although visualization will not be complete on any single coronal image, the entire ACL can be traced from its posterior to its anterior attachment in three to four images (Friedman and Jackson, 1996). A single axial view will also not show the entire ACL. The tibial attachment is rarely seen on these images. It is possible, however, to trace the majority of the ligament length in approximately forty-five images. The axial image is important because of its ability to provide cross-sectional information on the ligament, such as the width and location of potential tears (Friedman and Jackson, 1996).

Increasingly, optimal visualization of the ACL is being obtained through the use of the oblique sagittal image (Figure 5). This can be accomplished by either putting the knee into a position of slight external rotation, or rotating the image on the MR screen. Both Reicher, et al. (1985) and Buckwalter and Pennes (1990) have found that ten to twenty degrees of external rotation is optimal. They state that this position will make the entire ligament visible on one image or slice and will enhance the image quality.

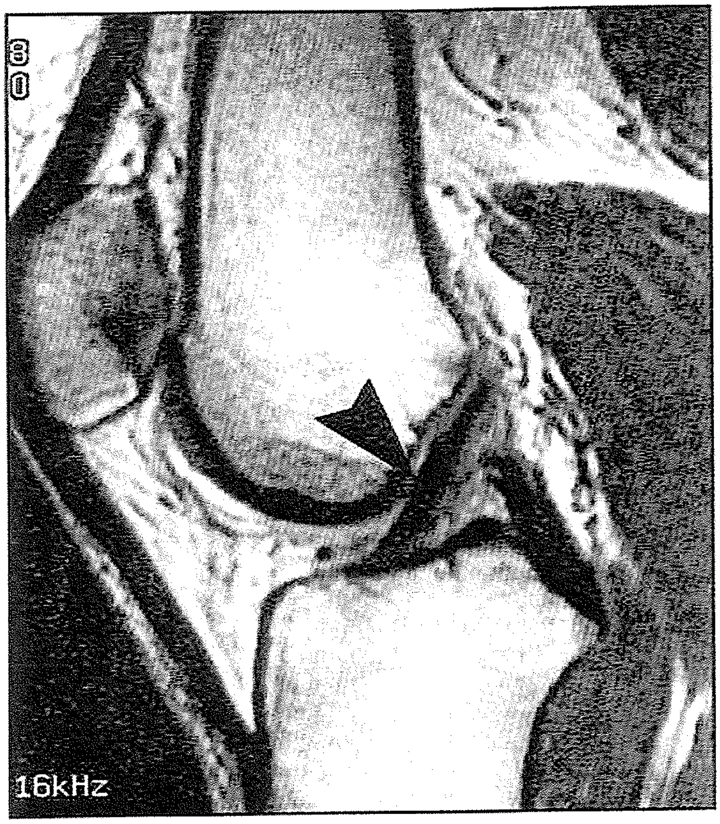


Figure 5. Oblique Sagittal Image of the Anterior Cruciate Ligament.
(Friedman and Jackson, 1996).

CHAPTER 3

METHODS

Collaboration

This study was a collaboration between the Institute for Biodiagnostics of the National Research Council of Canada and the University of Manitoba.

Subject Selection

The subjects for this study were 16 males and 18 females. Recruitment of volunteers was primarily from students at the University of Manitoba and the University of Winnipeg. Subjects were also recruited from the subject recruitment office at the National Research Council. Their volunteers were obtained primarily through poster advertising in various locations (subject recruitment office, university research information display boards) and word of mouth.

Subjects must have met the following inclusion criteria to be eligible for the study:

1. All subjects had to be in good health.
2. Subjects must have had no previous injury to the anterior cruciate ligament.
3. Subjects must have had no previous injury to the posterior cruciate ligament (PCL), medial collateral ligament (MCL), lateral collateral ligament (LCL), or either meniscus.
4. Subjects must not have had any previous knee surgery.
5. All subjects had to be between 17 and 30 years old.

These restrictions were imposed in an effort to minimize variability between subjects.

Any subjects with any of the following criteria were not eligible to participate in this MRI study:

1. Subjects who had metal objects inside their body which would exclude them from obtaining an MR examination, such as aneurysm and hemostatic clips; implanted electrodes and electrical devices including pacemakers; prosthetic heart valves; cerebral ventricular shunts; vascular access ports; intravascular coils, filters and stents; joint or limb replacements; orthopedic material and devices (i.e. rods, pins, screws, plates, steel mesh, steel wire).

2. Intraocular implants, ear implants, contraceptive diaphragms or intrauterine contraceptive agents, bullets, shrapnel or other foreign metal bodies like metal slivers.

3. Subjects with anxiety disorders such as claustrophobia, panic attacks or any disorders which could be exacerbated by stress.

4. Any subject who in the opinion of the screening physician or investigators, was at high risk for an exacerbation of a medical condition due to the added stress associated with participation in a research protocol.

5. Women who were pregnant, or if there was a chance the woman might be pregnant.

6. Any subject with past or present injuries to any of the following in the right knee: the anterior cruciate ligament, posterior cruciate ligament, medial collateral ligament, lateral collateral ligament, either meniscus.

7. Any subject with previous knee surgery.

Subject Recruitment

Subjects were recruited for this study by word of mouth and posters. Posters were placed in the Physical Education Departments of the University of Winnipeg and the University of Manitoba. There was also a posting at the National Research Council of Canada. All subjects were required to be free of any contraindicated medical conditions and must have passed a medical screening questionnaire administered by a physician. A list of physicians was provided, however, subjects may have had the screen completed by their own physician. The National Research Council was willing to pay a maximum of $22.00 to the physician for this consultation. The screen was designed to identify conditions which could make participation in an MRI study hazardous. These conditions include past or present medical conditions such as heart disease and anxiety disorders, and the presence of any metal objects in the body such a pacemaker, braces, or any metal implants of any kind.

Testing Location

The MR system was located in the MRI unit at the Health Sciences Centre, Winnipeg, Manitoba (Figure 6). The unit consisted of a reception area, a changing area for subjects, a separate magnet room, and a room for the technicians containing the MR system and analyzer. The magnet had a field strength of 1.5T, which is similar to most hospital scanners. The tunnel was 60 cm across and was open at both ends. The knee to be imaged was placed in a special MR coil which was shaped like a hollow cylinder of approximately 15 cm in diameter. The coil had separate top and bottom halves which were easily taken apart and padded for comfort.

The hours from approximately 1:00 pm until 7:00 pm each day were designated as research time for the MRI system at the Health Sciences Centre. All subjects were scheduled for imaging during this time. Subjects were booked into a one-and-one-half hour slot for testing, with an actual scanning time of approximately forty-five minutes. During the testing, the technician was in constant communication with the subject via a window and a two-way intercom.

In case of emergency, at least two members of the research team were certified in cardiopulmonary resuscitation and had participated in drills designed to ensure that all testing personnel were able to activate the Emergency Medical System.

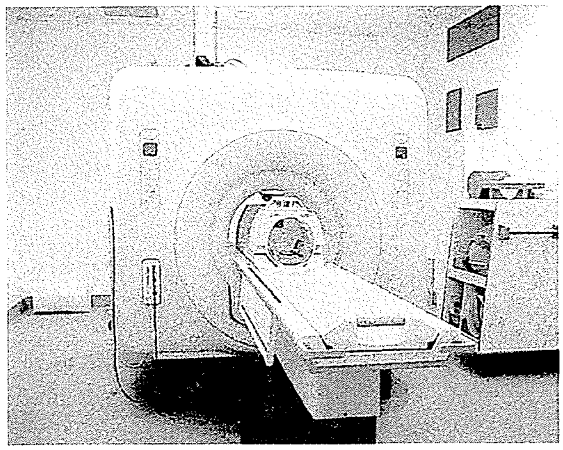


Figure 6. Magnetic Resonance Imaging System at Health Sciences Centre, Winnipeg, Manitoba.

Testing Protocols

All MRI tests were conducted by a trained MRI technician familiar with knee imaging techniques. The role of the present investigator was to perform all of the measurements from the images, and to collect and analyze the data; as well as to assist in recruiting and scheduling subjects.

Experimental design

This study was a cross-sectional study. Subjects had their right knee imaged on one occasion only for a maximum of 60 minutes. Due to a previously undisclosed partial ACL tear, the left knee of one subject was imaged. All imaging was carried out using the 1.5 T GE Signa Horizon LX MR system. Subjects were positioned supine with their right knee fully extended in a coil manufactured by GE specifically for knee imaging, and which is used for clinical MRI. Padding was placed around the knee to minimize motion and to make the subject as comfortable as possible. The leg and foot was also supported with padding and pillows. Subjects entered the magnet feet first so that their heads were just outside the magnet when the knee was placed at the magnet center.

Subject Height and Body Mass

The height and body mass of each subject was recorded based on the subject's self-report of height in feet and inches, and of weight in pounds. These were converted to height in centimeters and mass in kilograms.

Instructions to Subjects

The subjects were instructed that the study would involve one visit to the MRI unit at the Health Sciences Centre where they would have a Magnetic Resonance scan of their knee. The total time for the visit would be 1 1/2 hours with the actual scan taking approximately 45 minutes. The subjects were asked several questions prior to their appointment to make sure there were no metal objects in their body that would make it unsafe for them to have an MRI scan done.

At the appointment time, the subject reviewed a screening form with an investigator, the subject received information about the study, and was shown the MRI system. The subject was asked to sign a consent form to participate in the study. All of the subjects questions were answered and they agreed to participate before signing the form.

Before the actual scan, the subject was asked to change into clothing that did not contain metal. The subject was able to wear his or her own clothing if it was metal-free, or a hospital gown was provided.

For the MRI scan, the subject was positioned on their back and given earplugs or headphones to reduce the noise from the MRI scanner. The knee to be imaged was placed in a special coil, specifically for the knee, and was padded for comfort. The subject was then slid into the magnet, feet first, until his or her knee was at the centre of the magnet.

The MR operator was in constant communication with the subject during the scan through a two-way intercom. The set of images was obtained with the knee lying straight.

After the scan was completed, the subject was asked to fill out a questionnaire regarding his or her experience and any ill effects felt at the time of the study.

The subjects were informed that the study was completely confidential. The subjects were informed that they would receive $25 to cover any expenses they may have incurred to participate in the study. The subjects were informed that they had the right to withdraw from the study at any time and for any reason without penalty.

Imaging of the Intercondylar Notch

The MR protocol for imaging the intercondylar notch was initially as established by Herzog et al. (1994). This method employed a spin-echo technique to acquire proton density and T2-weighted axial and coronal images of the knee: TE = 30 and 90 msec, TR = 2400 msec, FOV = 16 cm, 2 averages, 256 x 154 matrix, 4 mm slice thickness, interslice gap of 0.4 mm. The plane of the axial sequence was perpendicular to the roof of the intercondylar notch, at the level of the popliteal recess (Figure 11). Notch measurements on the coronal image were made at the anterior outlet of the intercondylar notch. Measurements were made with the knee in full extension. This method was modified slightly during the testing to increase measurement accuracy, by reducing the slice thickness to 2 mm, FOV to 14 cm, and interslice gap to 0.0 mm as this was determined to be advantageous in improving image quality. This facilitated the most accurate measurements of the intercondylar notch by minimizing geometric distortion.

The image analysis tools available on the radiological workstation provided with the GE MR system were used to measure distances and angles from the images obtained. All values for the various distances and angles were generated by the computer analysis software to the nearest 0.1 mm. All measurements were performed by the present investigator. To determine the dimensions of the intercondylar notch, several measurements were performed. These included: M1 which was the width of the intercondylar notch or the distance between the femoral condyles. It was measured at three different locations on axial or cross-sectional images (Figure 7) and coronal or anterior view images (Figure 9): A, on a line through the centre of the popliteal recess (a hollow on the lateral sides of the femoral condyles for the proximal attachment of the popliteus muscle); B, on a line at the level of two thirds of the notch height; and C, on a line at the level of the articular margins of the medial and lateral femoral condyles. Another measurement was M2 - the intercondylar notch height which was the perpendicular distance from the apex of the notch to the horizontal line at the level of the articular margins of the medial and lateral femoral condyles. M3 was the intercondylar notch angle, the angle formed between the line connecting the apex of the notch and the articular margins of the femoral condyles (N). M4 was the lateral wall angle, the angle between the line from the apex of the notch to the lateral femoral condyle and the line which measures notch height (M2). M5 was the greatest medial to lateral dimension of the femoral condyles. M6 was the width of the femoral condyles at the level of the popliteal recess (Herzog, et al., 1994).

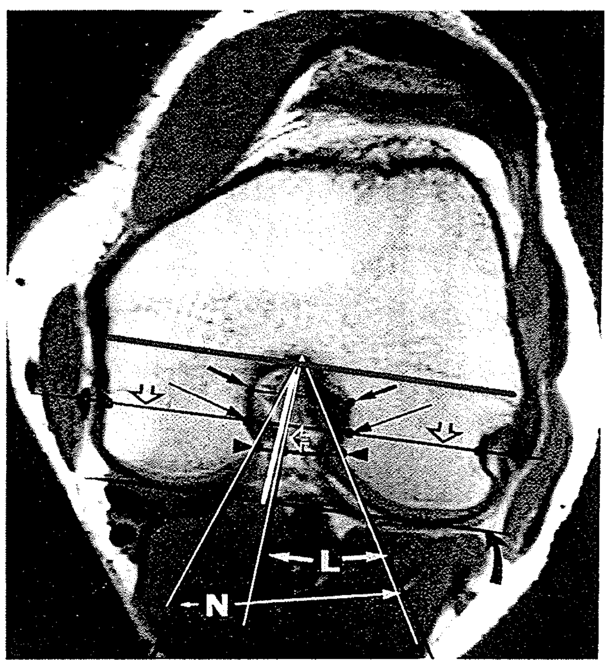


Figure 7. Measurements of the Intercondylar Notch on an Axial View MR Image. (Herzog, Silliman, Hutton, Rodkey, Steadman, 1994). Black arrowheads, the width of the intercondylar notch at the level of the medial and lateral femoral condyles; long black arrows, the width of the intercondylar notch at the popliteal recess; short black arrows, the width of the intercondylar notch at two-thirds notch height; open white arrow, notch height; N, the notch angle; L, the lateral wall angle; thick, solid black line, the greatest medial to lateral width of the femoral condyles; open black arrows, the width of the femoral condyles at the level of the popliteal recess; thick, solid white line, the notch depth.

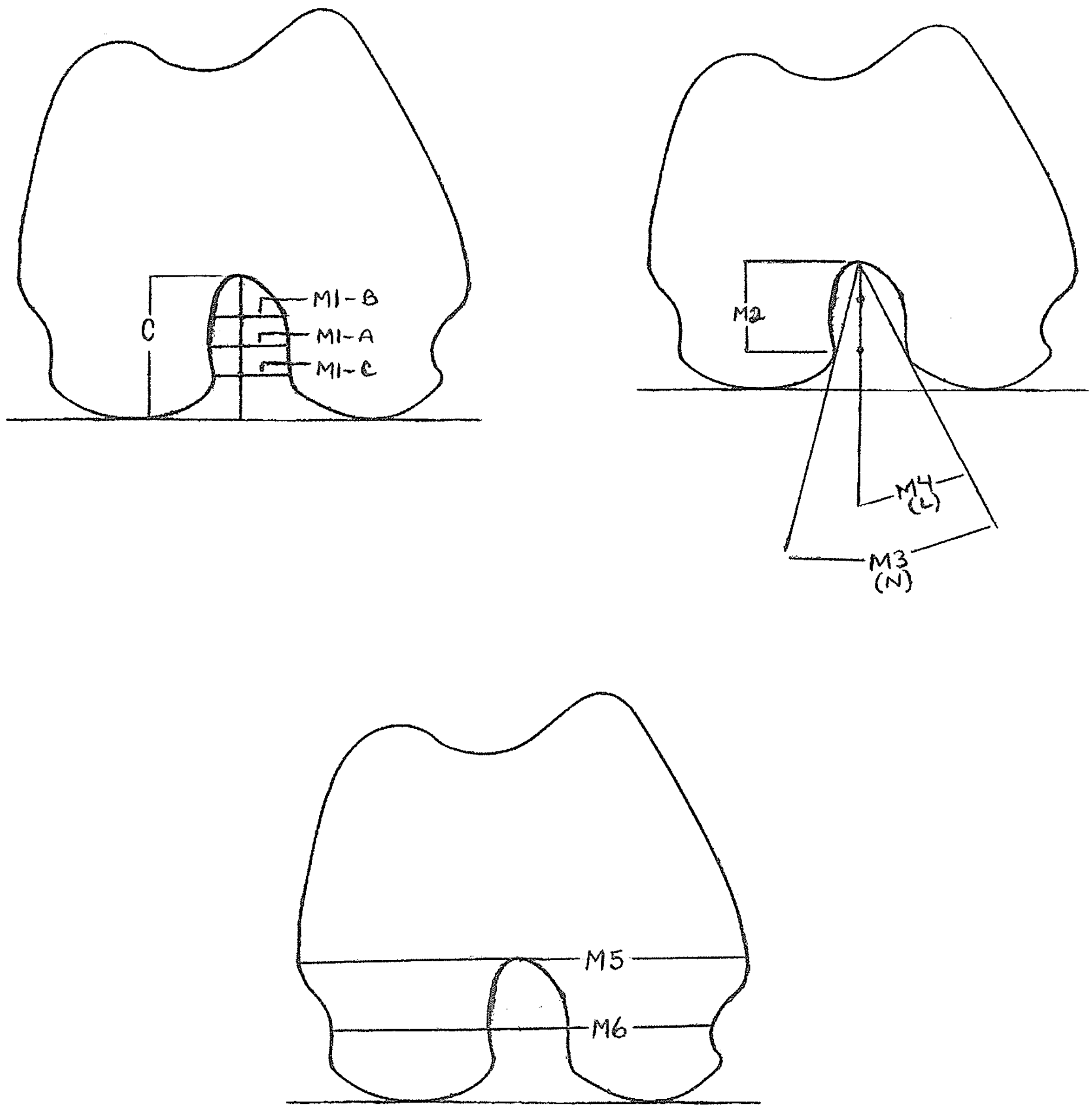


Figure 8. Diagrams adapted from Wada, et al. (1999) illustrating the various measurements of the intercondylar notch on an axial (cross-section) view MR image.

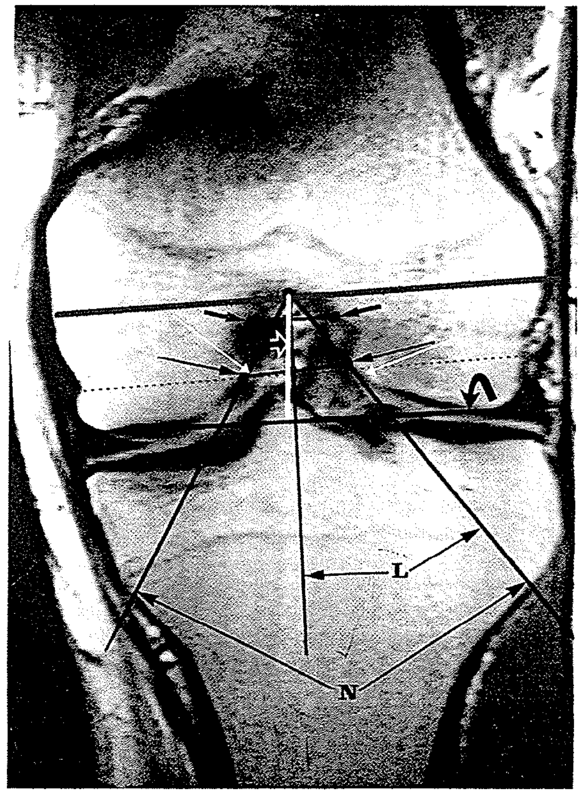


Figure 9. Measurements of the Intercondylar Notch on a Coronal View MR Image. (Herzog, Silliman, Hutton, Rodkey, Steadman, 1994) Long black arrows, the width of the intercondylar notch at the level of the medial and lateral femoral condyles; long white arrows, the width of the intercondylar notch at the popliteal recess; short black arrows, the width of the intercondylar notch at two-thirds notch height; open white arrow, notch height; N, the notch angle; L, the lateral wall angle; thick, solid black line, the greatest medial to lateral width of the femoral condyles; dashed black line, the width of the femoral condyles at the level of the popliteal recess; thick, solid white line, the notch height.

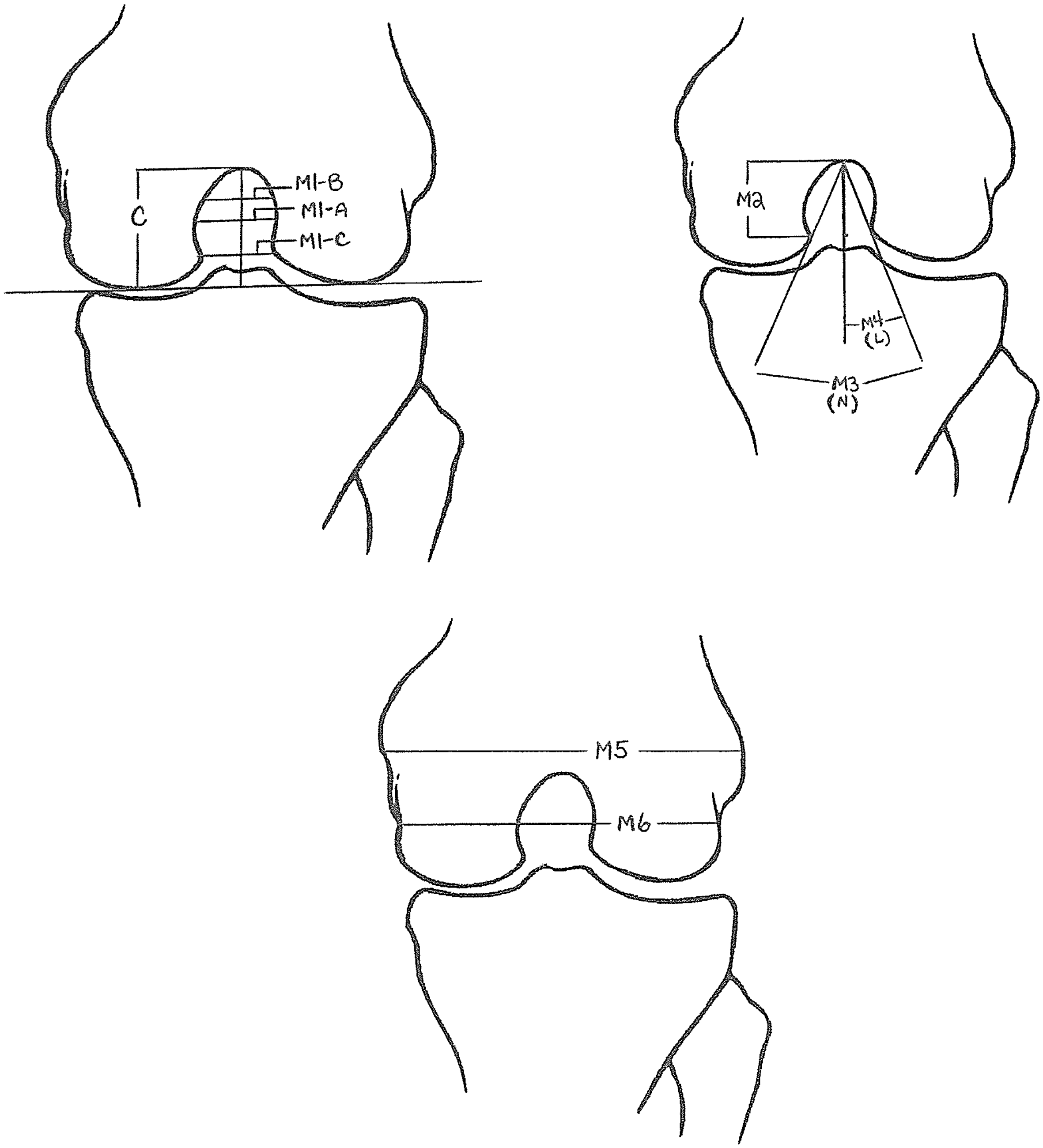


Figure 10. Diagrams adapted from Hutchinson and Ireland (1995) illustrating the measurements of the intercondylar notch on a coronal (anterior) view MR image.

The final measurement that was made of the notch was its depth (C) (refer to Figures 8 and 10). This is the maximum height of the notch as viewed on an axial image (Wada, Tatsuo, Baba, Asamoto, Nojyo, 1999).

These measurements were made using the same axial image used to make the other notch measurements (Figure 8). The image was obtained by using a slice perpendicular to the roof of the intercondylar notch at the level of the popliteal recess (Figure 11).

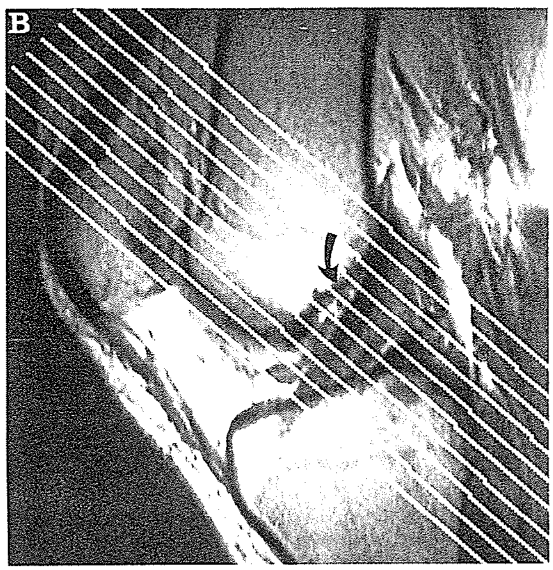


Figure 11. Imaging Plane for Axial Images (Herzog, et al., 1994).

Imaging of the Anterior Cruciate Ligament

Following the acquisition of the images of the notch, the anterior cruciate ligament was imaged in the right knee of each subject. Due to a previously undisclosed partial ACL tear, the left knee was imaged in one subject. All imaging was performed by a trained MRI technician.

The landmarks for all of the distance measurements included the entire length of the red measurement line on the distance measurement analysis tool on the radiological workstation.

Imaging of the anterior cruciate ligament to measure its length was performed with the knee in full extension, initially using a protocol developed by Do-Dai, Stracener, and Youngberg (1994) which enabled viewing of the ACL in its entirety. Their method involved acquiring an axial image at the level of the intercondylar notch. By angling the plane of imaging along the outer border of the lateral femoral condyle (LFC), an oblique sagittal image could be obtained which "consistently produced excellent depiction of the entire length of the ACL".

This protocol was modified during the initial imaging sessions by the MRI technician. Instead of using an axial image, the coronal image in which the ACL was most clearly seen was chosen. The plane of imaging was angled through the centre of the ligament. The image produced clearly depicted the ACL as a thick black band, versus the image produced by Do-Dai, et al. (1994) where the ACL appears as thin, thready bands. From the images obtained, the length of the ligament was determined by measuring the longest fibres (Figure 12).

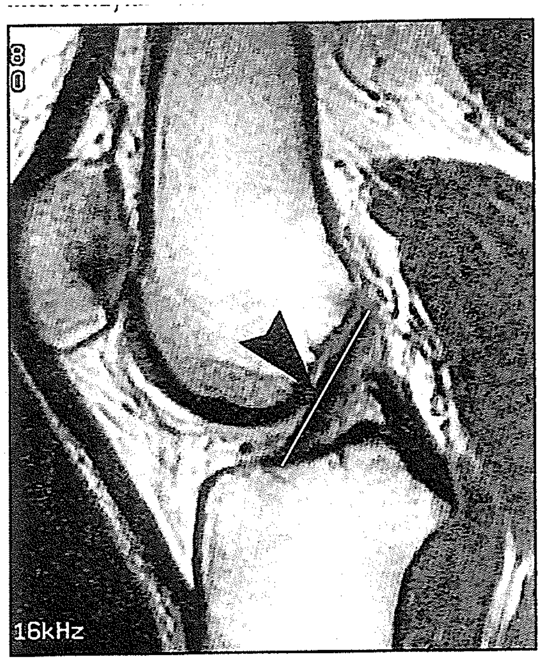


Figure 12. Magnetic Resonance Image (Sagittal Oblique View) of the ACL and Measurement of Ligament Length. (Friedman and Jackson, 1996).

Measurement of the width of the anterior cruciate ligament followed a protocol developed by Davis, Shelbourne, and Klootwyk (1999). A coronal slice was made where the ACL and PCL cross-at the level of the popliteal recess -as close as possible to the midsubstance of the ACL (Figure 13). It has been shown that the majority of ACL tears occur in the midsubstance of the ligament in young adults (Noyes and Grood, 1976; Kennedy, Hawkins, Willis, Danylchuk, 1976, Insall, 1979, Steadman and Rodkey, 1993)). The level of the popliteal recess was chosen here because these investigators believed that the ACL would tear through the midsubstance of the ligament, given the broad areas of attachment of the ligament, and the midsubstance should represent the narrowest portion of the ligament (Muneta, et al., 1997).

From the images obtained, the width of the ligament was measured at its narrowest point.

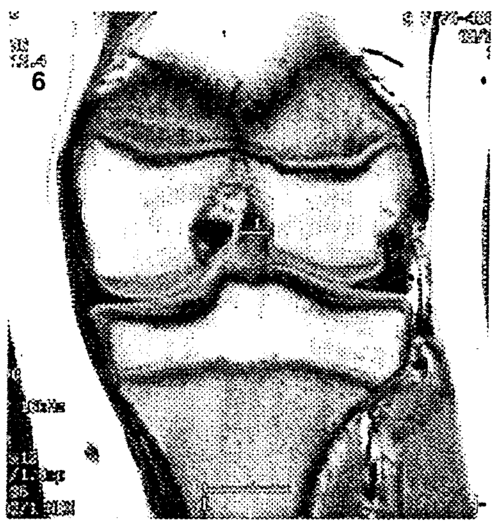
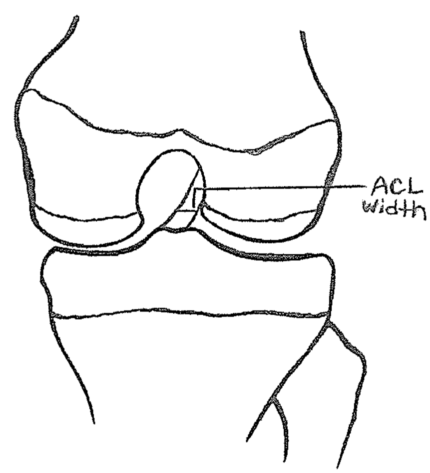


Fig. 13. MR Image to Measure ACL Width (Davis, et al. 1999).



Adapted from Hutchinson and Ireland (1995)

Finally, in order to measure the angle of pull of the ligament, a protocol designed by Reicher, Rauschning, Goid, Bassett, Lufkin, and Glen (1985) was used: spin-echo images, TE = 28 msec, TR = 500 msec, 256 x 256 matrix interpolated to 512 x 512.

Images were obtained in the axial plane at a level of 1.5 cm superior to the tibial plateau with the knee in full extension. The angle of pull of the ligament is the angle formed between a line perpendicular to the line along the inferior articular margins of the medial and lateral femoral condyles as viewed on an axial image and the line through the midsubstance of the ligament on the same axial image (Figure 14).

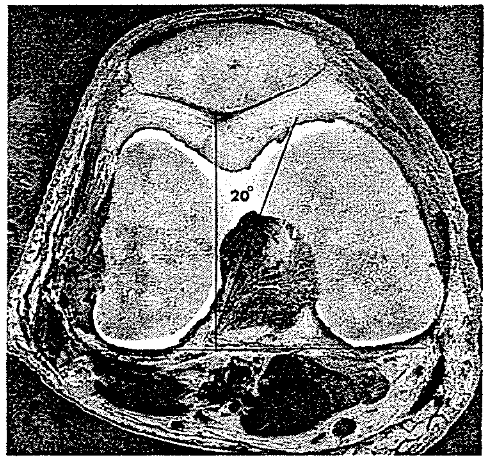


Figure 14. Angle of Pull of the Anterior Cruciate Ligament.
(Reicher, Rauschning, Goid, Bassett, Lufkin, Glen, 1985)

A series of between 150-200 individual images was produced for each subject. A minimum of five images was needed to make the required measurements for each subject. It was possible to perform some of the measurements on the same image. The images required were as follows:

- one axial image (level of the popliteal recess) - for notch measurements
- one coronal image (level of the anterior outlet of the notch) - for notch measurements
- one oblique sagittal image (imaging plane through the centre of the ligament on a coronal image) - to measure ACL length
- one coronal image (level of the popliteal recess) - to measure ACL width
- one axial image (1.5 cm superior to the tibial plateau) - to measure angle of pull of the ACL

It was one role of the current investigator to select the most appropriate images to analyze.

The images to be analyzed were determined based on protocols by Herzog, et al. (1994), Davis, et al. (1999), Reicher, et al. (1985), and Do-Dai, et al. (1994). The protocol of Do-Dai, et al. (1994) was modified during the initial imaging sessions by the MRI technologist to produce better image quality. Measurement of the various distances and angles of the notch were made on an axial MR image at the level of the popliteal recess, and on a coronal image at the level of the anterior outlet of the notch. Measurement of the ACL width was made at the level of the popliteal recess on a coronal MR image. The angle of pull of the ACL was measured on an axial image at the level of 1.5 cm superior to the tibial plateau. The length of the ACL was measured on a sagittal oblique image obtained from a coronal image at the anterior outlet of the notch.

The MR system software enabled viewing of three imaging planes simultaneously (sagittal, coronal, and axial). The plane of imaging was placed over the appropriate scout image. Each imaging plane consisted of between 7 to 10 individual images or slices. The appropriate slice at the correct level was then selected from these individual images by noting the number of the image or slice.

All measurements of the various distances and angles of the intercondylar notch and the ACL were repeated three times to ensure their reliability.

Data Analysis

All measurements were performed by the current investigator using the MRI analysis software provided with the machine. All values for the various distances and angles were generated by the computer analysis software to the nearest 0.1mm. The measurements were then entered into a statistical analysis program. The statistics programs used were the Excel spreadsheet program and SPSS Version 10.0 on an IBM computer.

The first step in the analysis of the data was to calculate the means and standard deviations for all of the notch measurements (M1, M2, M3, M4, M5, M6, C) and all of the ligament measurements (L, W, angle of pull). This was done for both the male and female groups.

The final statistical analysis consisted of four parts. Part one was to determine if there was an absolute difference between notch dimensions and ligament measurements in males as compared to females. This was done using an analysis of variance (ANOVA). It assumes a normal distribution and that the variances of the two samples are equal. The variance for each notch and ligament measurement were compared, male versus female, for significant differences. The level of significance was set at $p<0.05$. The final "F" value for each of the tests was compared against the appropriate critical value from the F table. A "F" value exceeding the appropriate critical value would indicate significant differences between the groups.

This portion of the analysis was designed to answer the following questions. How did the intercondylar notch configuration differ between males and females? The literature reports both significant (Shelbourne, et al., 1998; Souryal, et al., 1993) and non-significant (Anderson, et al., 1987; LaPrade and Burnett, 1994) differences between male and female measurements. These studies primarily address notch width. They express this width as a ratio of the notch width to the femoral bicondylar width, the notch width index. According to Shelbourne, et al. (1998), this ratio may produce results that may not be sensitive since it does not account for anthropometric differences in that it assumes that notch width and bicondylar width correlate directly. Shelbourne, et al., 1998) found that they do not. Notch width did not directly increase with increasing height for men or women, however, femoral bicondylar width did.

Specifically, this analysis was to look at how notch width, notch height, notch angle, lateral wall angle, condyle width, and notch depth, differ between males and females. Did all of the measurements differ between the sexes? Were the measurements consistently larger or smaller for men or women or was there no difference? Were the measurements different from what was reported in the literature regarding what constitutes a narrow or wide notch?

Two, how did the size of the ACL differ between males and females? Did males or females have longer or shorter ligaments? Was the ligament wider or narrower in women than men? Did the ACL pull at a different angle (either steeper or flatter) in males or females? Were the measurements different from those reported in previous studies? Longer ligaments should be less stiff and should require a longer elongation before failure, while shorter ligaments should be stiffer and there should be less of a length change before failure (Butler, Grood, Noyes, and Zernicke, 1978). Ligaments with increased width should have more fibres to carry loads. These ligaments should be stiffer and stronger and able to withstand larger forces (Butler, et al., 1978).

The angle of pull of the ligament was important because if the angle was too acute (straight up) or obtuse (flat), it might affect the ability of the ligament to withstand the rotational stresses of the tibia on the femur.

Part two was to determine if intercondylar notch size was related to the size of the anterior cruciate ligament. This analysis was accomplished through the use of multiple correlations (Pearson correlation coefficient). The correlation coefficient is an index of the tendency of two continuous measurements to vary together. The absolute value of the correlation coefficient can range from a minimum of 0 to a maximum of 1. The sign of the correlation coefficient shows the direction of the relationship. Each of the notch measurements (M1, M2, M3, M4, M5, M6, C) was correlated with each of the ligament measurements (L, W, angle of pull). The level of significance was set at $p<0.05$. The final "r" value was tested against critical values. An "r" value exceeding the critical value should give evidence of a significant relationship between the variables.

Several questions were to be answered here. One, was notch size related to ACL length for males and for females? Two, was notch size related to ACL width for males and for females? Three, was notch size related to the angle of pull of the ligament for males and for females? What if the male and female results were combined? Would notch size still be related to ACL length, width, and angle of pull? Also important is the type of correlation. Were the correlations positive, negative, or was there no relationship?

Part three of the analysis was to determine if there was a predictive value of the size of anatomical structures. Could the width, height, and opening angles of the intercondylar notch be predicted from other measures of notch size or ACL size? Could the femoral bicondylar width be predicted based on the size of the notch or the ACL? Could the size and angle of pull of the ACL be predicted from notch measurements? Do gender, height, and body mass have any predictive value? Could notch or ACL size on an axial view MR image be predicted from predictive factors on a corresponding coronal view image?

This analysis was accomplished through the use of a stepwise multiple linear regression. The stepwise multiple linear regression describes the relationship between an outcome or dependent variable and a number of potential explanatory variables. The explanatory variable that can explain the largest proportion of the dependent variable is indicated first in the model, followed by the remaining explanatory variables in descending order (Hassard, 1991). The final "F" value for each of the tests was compared against the appropriate critical value from the F table for significance.

Given the results of Davis, et al. (1999) which demonstrated that notch width alone could be an indicator/predictor of ACL width, it seemed possible that notch dimensions might also have been able to predict ligament length or angle of pull.

Davis, et al. (1999) concluded that patients with narrow notches have narrower ACL widths. Butler, et al. (1978) described that a narrower ligament should be less stiff and have less strength. Given this, a small, narrow notch should contain a narrow and weaker ligament. Further study, however, is needed to test ACL size and strength, which is beyond the scope of the present paper.

Part four of the analysis was to determine if notch size was related to subject height or body mass, and to determine if ACL size was related to subject height or body mass. This analysis was accomplished through the use of multiple correlations (Pearson correlation coefficient). Several questions were to be answered here. Was notch size related to height and mass for males? Was notch size related to height and mass for females? If the results for males and females were combined, would notch size be related to height and body mass? However, since the height and body mass were not obtained from direct measurement but rather from self-report, the validity of these results is questionable. This section of results is reported for illustrative purposes only and should be interpreted with great caution.

Ethical Considerations

Within the scope of this study, there were several ethical factors to consider. First and foremost was the protection of the rights of the subjects. All subjects were given a copy of the research study summary. They were told what the study is about and why MRI was chosen. As well, they were instructed regarding exactly what would happen during the imaging session and were shown all of the equipment. During the imaging session, the subject was in constant communication with the MR technician via a two-way intercom. Subjects were also informed of the potential benefits of the study and any associated risks of using MRI. Any questions subjects had about the study were answered and subjects were free to withdraw from the study at any time without penalty.

Subjects names were not used in the report but rather an identification number, and all data was kept completely confidential. At any time, any subject could request a copy of the complete scientific protocol for the study. They were also entitled to know the overall scientific and technical results at the end of the project.

Finally, all subjects were required to have a screening questionnaire completed by a physician. A list of physicians was provided, however, subjects could have the screen completed by their own physician. Subjects were also required to read and sign an informed consent form. They were also given an opportunity to fill out a questionnaire at the end of their imaging session to comment on the imaging session.

Pilot Testing

Pilot testing was performed on November 8, 1999 at the Magnetic Resonance Imaging Unit at the Health Sciences Centre, Winnipeg, Manitoba. The subject was a twenty-seven year old male with no previous knee injuries or surgery. All imaging was completed within a two-and-one half hour period. All imaging was performed by a trained MRI technician.

The subject was positioned supine in the magnet. The knee was positioned in full extension in the knee coil which was padded for comfort. The subject was also given a pillow for his head. The subject entered the magnet feet first with the knee placed at the centre of the magnet. The subject's head remained outside the magnet at all times.

After the testing session, all images were transferred to the adjacent radiological workstation where measurements were performed to determine the various distances and angles. All measurements were repeated twice to confirm their accuracy. All measurements were performed by the current investigator who had previously been trained in the measurement techniques.

Results of Pilot Testing

The measurements made from the MRI testing session using a single male subject are reported in Table 3.1. The mean measurements from current research refer to studies by Herzog, et al. (1994), Staeubli, et al. (1999), Wada, et al. (1999), Davis, et al. (1999), Reicher, et al. (1985), Butler, et al. (1992), and Noyes and Grood (1976).

Table 3.1. Results of Pilot Testing

	Male Subject (Measurement #1)	Male Subject (Repeated Measurement)	Data From Existing Studies
M1 (Notch Width-Axial View) a) at popliteal recess b) at 2/3 notch height c) through inferior articular margins of femoral condyles	 21.4 mm 16.2 mm 19.4 mm	 21.3 mm 17.1 mm 19.9 mm	 21.0+/- 2.4 mm (Herzog, et al., 1994) 15.3 +/- 3.5 mm (Herzog, et al., 1994) 17.9 +/- 3.4 mm (Herzog, et al., 1994)
M2 (Notch Height)	19.7 mm	20.1 mm	19.4 +/- 3.0 mm (Herzog, et al., 1994)
M3 (Notch Angle)	43°	43°	48.9° +/- 6.8° (Herzog, et al., 1994)
M4 (Lateral Wall Angle)	22°	24°	21.5° +/- 7.0° (Herzog, et al., 1994)
M5 (Greatest Medial to Lateral Dimension of Femoral Condyles)	80.4 mm	80.2 mm	72.9 +/- 3.9 mm (Herzog, et al., 1994)
M6 (Femoral Condyle Width at Popliteal Recess)	71.9 mm	71.6 mm	68.4 +/- 3.7 mm (Herzog, et al., 1994)
C (Notch Depth)	32.9 mm	33.0 mm	29.5mm (Group A) (Wada, et al., 1999) 25.0 mm (Group B) (Wada, et al., 1999) 20.0 mm (Group C) (Wada, et al., 1999)
ACL Length	36.2 mm	36.4 mm	AMB=32.5 mm (Butler, et al., 1992) ALB=28.6 mm (Butler, et al., 1992) 26.9 mm (Noyes and Grood, 1976)
ACL Width	5.9 mm	5.9 mm	6.1 mm (male) (Staeubli, et al., 1999) 5.2 mm (female) (Staeubli, et al., 1999) 7.1 mm (male) (Davis, et al., 1999) 5.7 mm (female) (Davis, et al., 1999)
ACL Angle of Pull	20°	21°	20° (Reicher, et al., 1985)

CHAPTER 4

RESULTS

This chapter will report the results of the investigation on the relationship between intercondylar notch size and the size of the anterior cruciate ligament in males and females. The first section reports the results of measuring the intercondylar notch and femoral condyles, and the anterior cruciate ligament on axial and coronal magnetic resonance images. The second section analyzes the relationship between the size of the intercondylar notch and femoral condyles and the size and angle of pull of the ACL. Section three reports on the ability to predict the notch and size and ACL size for males and females combined. The fourth and final section analyzes the relationship between intercondylar notch size, ACL size and subject height and body mass.

Subjects

Thirty-four subjects, 16 male and 18 female, were involved in this study. Subjects were students at the University of Manitoba and University of Winnipeg, and were also volunteers recruited from the subject recruitment office of the National Research Council of Canada. All subjects were in good health. All subjects were to have had no previous knee injuries or surgeries. One male subject presented with a previous history of a partial ACL tear in the right knee. This injury had gone undisclosed through the screening process and was only revealed when the subject arrived for the imaging session. The left knee of this subject was imaged.

The group of 16 males ranged in age from 22 to 29 (mean = 25.06, SD = 2.11). Their height and mass (self-reported) ranged from 165.1 to 190.5 centimeters (mean = 179.86, SD = 6.95) and 56.82 to 118.18 kilograms (mean = 78.92, SD = 18.17). The female group of 18 ranged in age from 19 to 30 (mean = 23.94, SD = 3.81). Their height and mass (self-reported) ranged from 152.4 to 185.42 centimeters (mean = 168.91, SD = 7.96) and 45.45 to 90.91 kilograms (mean = 69.70, SD = 13.46).

The comparison of the mean demographic data for male and female subjects is reported in Table 4.1. No statistically significant differences were found between males and females with regard to age. But when examining height and body mass, statistically significant differences were noted. The male group was significantly taller ($p = 0.001$) and heavier ($p = 0.0499$) than the female group.

Table 4.1 Comparison of Mean Demographic Values for Males and Females

	Males	Females	T Value	P Value
Age (years)	25.06	23.94	1.04	0.307
Height (cm)	179.86	168.91	4.25 **	0.001
Mass (kg)	78.92	69.70	1.69 *	0.0499

* Indicates significance ($p<0.05$)
** Indicates significance ($p<0.01$)

Measurement of the Intercondylar Notch and Femoral Condyles

Measurement of the dimensions of the intercondylar notch and femoral condyles was performed on both axial and coronal view MR images. The axial image was acquired at the level of the popliteal recess. The comparison of the mean measurements is reported in Table 4.2 for each of the following: M1-A - notch width at the level of the popliteal recess; M1-B - notch width at two-thirds notch height; M1-C - notch width at the articular margins of the femoral condyles; M2 - notch height, M3 - notch angle, M4 - lateral wall angle, M5 - greatest medial to lateral dimension of the femoral condyles, M6 - width of the femoral condyles at the level of the popliteal recess, and C - notch depth.

Table 4.2 Comparison of Mean Axial Intercondylar Notch and Femoral Condyle Measurements for Males and Females (mm). (Standard Deviation)

	Males	Females	F Value	P Value
M1-A	24.1 (2.44)	20.1 (1.80)	31.21 **	3.6E-06
M1-B	17.9 (2.30)	15.3 (1.81)	13.11 **	0.001
M1-C	22.1 (3.33)	18.7 (2.83)	10.46 **	0.003
M2	25.2 (3.30)	22.9 (1.28)	6.94 *	0.013
M3	44.6 (6.52)	43.5 (5.69)	0.27	0.605
M4	23.7 (5.76)	25.1 (4.30)	0.66	0.424
M5	80.3 (3.69)	70.2 (3.02)	76.96 **	5.04E-10
M6	75.1 (3.79)	66.0 (2.85)	63.05 **	4.61E-09
C	33.0 (2.14)	30.5 (2.68)	9.24 **	0.005

* Indicates significance ($p<0.05$)
** Indicates significance ($p<0.01$)

Measurement of the various distances and angles of the intercondylar notch and femoral condyles was performed on a coronal image acquired at the level of the anterior outlet of the notch. The comparison of the mean measurements are reported in Table 4.3.

Table 4.3 Comparison of Mean Coronal Intercondylar Notch and Femoral Condyle Measurements for Males and Females (mm). (Standard Deviation)

	Males	Females	F Value	P Value
M1-A	21.8 (2.31)	18.0 (1.78)	28.33 **	7.78E-06
M1-B	16.4 (1.79)	14.2 (1.60)	15.46 **	0.0004
M1-C	19.3 (3.34)	16.1 (2.30)	10.71 **	0.003
M2	22.0 (3.69)	20.1 (2.49)	3.31	0.078
M3	45.1 (8.89)	43.5 (9.35)	0.26	0.614
M4	25.1 (4.88)	25.8 (6.84)	0.12	0.729
M5	83.3 (3.65)	73.9 (3.39)	61.11 **	6.45E-09
M6	74.5 (3.76)	66.1 (2.96)	52.69 **	3.01E-08
C	29.6 (3.52)	28.0 (2.83)	2.26	0.143

* Indicates significance ($p<0.05$)
** Indicates significance ($p<0.01$)

Measurement of the Anterior Cruciate Ligament

The comparison of the length, width, and angle of pull of the anterior cruciate ligament between males and females is reported in Table 4.4. Males had significantly longer and slightly (but not significantly) wider ligaments. In females, the ACL pulled at a slightly greater angle than in males. This difference was not significantly different.

Table 4.4 Comparison of Mean Anterior Cruciate Ligament Measurements for Males and Females (mm). (Standard Deviation)

	Males	Females	F Value	P Value
Length	39.8 (2.29)	34.5 (2.74)	36.87 **	8.82E-07
Width	4.7 (0.78)	4.7 (0.75)	0.03	0.870
Angle of Pull	25.6 (5.98)	27.0 (6.38)	0.44	0.513

* Indicates significance ($p<0.05$)
** Indicates significance ($p<0.01$)

Intercondylar Notch Size, Femoral Condyle Size and Anterior Cruciate Ligament Size

The Pearson correlation coefficient was used to describe the relationship between the size of the intercondylar notch and femoral condyles as measured on both axial and coronal MR images, and the size and angle of pull of the ACL. The results of the analyses are presented in Tables 4.5, 4.6, 4.7, 4.8, 4.9, and 4.10.

According to Table 4.5a, the correlations between intercondylar notch and femoral condyle measurements on axial view MR images and ACL length demonstrated no statistically significant relationships, although for the male group, the correlation between lateral wall angle ($r = -0.42$, $p = 0.107$) and the greatest medial to lateral width of the femoral condyles to ACL length ($r = 0.47$, $p = 0.066$) did approach significance. For the female group, the correlation of notch width at the articular margins of the femoral condyles to ACL length also approached significance ($r = 0.42$, $p = 0.082$). The remainder of the correlations indicated weak to virtually non-existent relationships.

The correlations between intercondylar notch and femoral condyle measurements on coronal MR images and ACL length for both males and females are reported in Table 4.5b. The results indicate only one significant correlation - between the greatest width of the femoral condyles and ACL length ($r = 0.50$, $p = 0.048$) for the male group. Correlations between ligament length and the following three measurements - notch angle, lateral wall angle, and notch depth, all approached significance. For the female group, the r values for the correlations between ACL length and notch width at two-thirds notch height and greatest width of the femoral condyles, were close to significance, with the remainder showing only weak relationships.

There were two correlations for the male group that produced similar r values on the axial and coronal views. First was the lateral wall angle. Although neither of the correlations reached significance, the r values were similar at -0.42 on the axial view and -0.40 on the coronal view. Second was the greatest femoral bicondylar width, which had a significant r value of 0.50 ($p = 0.048$) on the coronal view and an r value close to significance on the axial view at 0.47 ($p = 0.066$). For the female group there were also two correlations which produced similar r values on the axial and coronal views. First was the notch width at the level of the popliteal recess with an r value of 0.21 on the axial view and 0.25 on the coronal view. Neither of these correlations were statistically significant. Second was the greatest femoral bicondylar width. The r values did not reach significance but were similar with an r value of 0.38 and 0.40 on the axial and coronal views respectively.

Table 4.5 Correlation of Intercondylar Notch and Femoral Condyle Measurements to ACL Length for Males and Females.

a. Axial Notch and Femoral Condyle Measurements

Males				Females			
Mean Axial Measurement (mm)		Pearson r	P Value	Mean Axial Measurement (mm)		Pearson r	P Value
M1-A	24.1	-0.15	.575	M1-A	20.1	0.21	.395
M1-B	17.9	0.19	.487	M1-B	15.3	0.35	.156
M1-C	22.1	-0.13	.635	M1-C	18.7	0.42	.082
M2	25.2	0.24	.378	M2	22.9	0.34	.165
M3	44.6	-0.33	.209	M3	43.5	0.34	.172
M4	23.7	-0.42	.107	M4	25.1	-0.01	.978
M5	80.3	0.47	.066	M5	70.2	0.38	.124
M6	75.1	0.29	.268	M6	66.0	0.32	.193
C	33.0	0.17	.519	C	30.5	-0.001	.997

b. Coronal Notch and Femoral Condyle Measurements

Males				Females			
Mean Coronal Measurement (mm)		Pearson r	P Value	Mean Coronal Measurement (mm)		Pearson r	P Value
M1-A	21.8	0.16	.546	M1-A	18.0	0.25	.311
M1-B	16.4	0.14	.604	M1-B	14.2	0.43	.076
M1-C	19.3	0.21	.440	M1-C	16.1	0.32	.194
M2	22.0	0.34	.197	M2	20.1	0.18	.487
M3	45.1	-0.44	.089	M3	43.5	-0.18	.475
M4	25.1	-0.40	.128	M4	25.8	-0.13	.600
M5	83.3	0.50 *	.048	M5	73.9	0.40	.098
M6	74.5	0.34	.192	M6	66.1	0.38	.121
C	29.6	0.47	.065	C	28.0	0.28	.268

* Indicates significance ($p<0.05$)
** Indicates significance ($p<0.01$)

The results of the correlations between notch and femoral condyle measurements and ACL length for males and females combined are shown in Table 4.6. Table 4.6a shows seven significant correlations on the axial view. These were found for notch width at the level of the popliteal recess ($r = 0.529$, $p = 0.001$), notch width at two-thirds notch height ($r = 0.546$, $p = 0.001$), notch width at the articular margins ($r = 0.460$, $p = 0.006$), notch height ($r = 0.456$, $p = 0.007$), the greatest femoral bicondylar width ($r = 0.768$, $p = 0.001$), femoral bicondylar width at the level of the popliteal recess ($r = 0.715$, $p = 0.001$), and notch depth ($r = 0.385$, $p = 0.025$). Table 4.6b also shows seven significant correlations. These were similar to those found on the axial view. Significant correlations were found for notch width at the level of the popliteal recess ($r = 0.603$, $p = 0.001$), notch width at two-thirds notch height ($r = 0.583$, $p = 0.001$), notch width at the level of the articular margins of the medial and lateral femoral condyles ($r = 0.515$, $p = 0.002$), notch height ($r = 0.383$, $p = 0.025$), greatest femoral bicondylar width ($r = 0.770$, $p = 0.001$), femoral bicondylar width at the level of the popliteal recess ($r = 0.725$, $p = 0.001$), and notch depth ($r = 0.426$, $p = 0.012$). The only difference between the correlations found on the axial view and the coronal view was the significance level of the correlation of notch height. On the axial view the correlation was significant at $p<0.01$ level and on the coronal view the correlation was significant at the $p<0.05$ level. No significant correlations were found for notch angle or lateral wall angle on either the axial or coronal view.

Table 4.6 Correlation of Intercondylar Notch and Femoral Condyle Measurements to ACL Length for Males and Females Combined.

a. Axial Notch and Femoral Condyle Measurements

Mean Axial Measurement (mm)		Pearson r	P value
M1-A	21.9	0.529 **	0.001
M1-B	16.5	0.546 **	0.001
M1-C	20.3	0.460 **	0.006
M2	23.9	0.456 **	0.007
M3	44.0	0.088	0.620
M4	24.4	-0.242	0.167
M5	75.0	0.768 **	0.001
M6	70.3	0.715 **	0.001
C	31.7	0.385 *	0.025

b. Coronal Notch and Femoral Condyle Measurements

Mean Coronal Measurement (mm)		Pearson r	P value
M1-A	19.8	0.603 **	0.001
M1-B	15.2	0.583 **	0.001
M1-C	17.6	0.515 **	0.002
M2	20.9	0.383 *	0.025
M3	44.2	-0.128	0.469
M4	25.4	-0.197	0.265
M5	78.3	0.770 **	0.001
M6	70.0	0.725 **	0.001
C	28.8	0.426 *	0.012

* Indicates significance ($p<0.05$)
** Indicates significance ($p<0.01$)

The results of the correlations between notch and femoral condyle measurements and ACL width are shown in Table 4.7. Comparing ACL width with axial notch measurements, two statistically significant correlations were found. The first, for the males, was a positive correlation between the greatest width of the femoral condyles and the width of the ACL ($r = 0.60$, $p = 0.015$). The second was in the female group. Again, it was a positive correlation - between ACL width and the width of the notch at two-thirds its height ($r = 0.61$, $p = 0.008$). The remaining correlations for both males and females were all statistically non-significant, demonstrating very weak to virtually non-existent relationships between the variables. The correlation between condyle width at the level of the popliteal recess and ACL width for males did approach significance ($r = 0.41$, $p = 0.118$).

The correlations between the various coronal notch and femoral condyle measurements and ACL width did not indicate any significant relationships for the female group. The results show two weak relationships - the width of the ligament with the width of the notch at the articular margins of the femoral condyles ($r = 0.34$, $p = 0.168$), and the width of the ligament with the lateral wall angle ($r = 0.33$, $p = 0.188$).

Two statistically significant correlations were found for the male group. The first was a positive correlation between ACL width and notch height ($r = 0.52$, $p = 0.038$). The second was a stronger positive correlation - this time between ACL width and notch depth ($r = 0.69$, $p = 0.003$).

Table 4.7 Correlation of Intercondylar Notch and Femoral Condyle Measurements to ACL Width for Males and Females.

a. Axial Notch and Femoral Condyle Measurements

Males				Females			
Mean Axial Measurement (mm)		Pearson r	P Value	Mean Axial Measurement (mm)		Pearson r	P Value
M1-A	24.1	-0.17	.533	M1-A	20.1	-0.02	.952
M1-B	17.9	-0.16	.553	M1-B	15.3	0.61 **	.008
M1-C	22.1	0.02	.954	M1-C	18.7	0.15	.563
M2	25.2	-0.04	.896	M2	22.9	-0.13	.615
M3	44.6	0.10	.708	M3	43.5	0.21	.404
M4	23.7	0.23	.386	M4	25.1	-0.10	.717
M5	80.3	0.60 **	.015	M5	70.2	-0.10	.700
M6	75.1	0.41	.118	M6	66.0	-0.10	.717
C	33.0	-0.30	.251	C	30.5	0.07	.781

b. Coronal Notch and Femoral Condyle Measurements

Males: Mean Coronal Measurement (mm)		Pearson r	P Value	Females: Mean Coronal Measurement (mm)		Pearson r	P Value
M1-A	21.8	0.16	.566	M1-A	18.0	0.18	.487
M1-B	16.4	0.02	.948	M1-B	14.2	-0.12	.642
M1-C	19.3	0.32	.223	M1-C	16.1	0.34	.168
M2	22.0	0.52 *	.038	M2	20.1	-0.27	.281
M3	45.1	-0.16	.541	M3	43.5	0.14	.588
M4	25.1	-0.13	.637	M4	25.8	0.33	.188
M5	83.3	0.44	.086	M5	73.9	-0.05	.855
M6	74.5	0.35	.182	M6	66.1	0.12	.643
C	29.6	0.69 **	.003	C	28.0	-0.18	.473

* Indicates significance ($p<0.05$)
** Indicates significance ($p<0.01$)

The results of the correlations between notch and femoral condyle measurements and ACL width for males and females combined are reported in Table 4.8. No significant correlations were found on either the axial view or the coronal view, and no matches in r values between axial and coronal views were observed.

Table 4.8 Correlation of Intercondylar Notch and Femoral Condyle Measurements to ACL Width for Males and Females Combined.

a. Axial Notch and Femoral Condyle Measurements

Mean Axial Measurement (mm)		Pearson r	P value
M1-A	21.9	-0.050	0.780
M1-B	16.5	0.179	0.311
M1-C	20.3	0.083	0.642
M2	23.9	-0.040	0.822
M3	44.0	0.156	0.377
M4	24.4	0.080	0.651
M5	75.0	0.169	0.341
M6	70.3	0.128	0.471
C	31.7	-0.063	0.725

b. Coronal Notch and Femoral Condyle Measurements

Mean Coronal Measurement (mm)		Pearson r	P value
M1-A	19.8	0.139	0.434
M1-B	15.2	-0.024	0.893
M1-C	17.6	0.296	0.089
M2	20.9	0.188	0.287
M3	44.2	-0.001	0.998
M4	25.4	0.142	0.423
M5	78.3	0.138	0.436
M6	70.0	0.171	0.333
C	28.8	0.277	0.113

* Indicates significance ($p<0.05$)
** Indicates significance ($p<0.01$)

The analysis of the relationship between intercondylar notch and femoral condyle size and the angle of pull of the ACL is shown in Table 4.9. The first part of this analysis correlates the angle of pull to notch measurements obtained from axial view MR images.

The table shows three statistically significant correlations for males. The first shows a positive correlation between the angle of pull of the ligament and the notch width at the level of the popliteal recess ($r = 0.56$, $p = 0.023$). The second is also a positive correlation, this time between the angle of pull of the ligament and the greatest width of the femoral condyles ($r = 0.52$, $p = 0.041$). The third is a strong positive relationship between the angle of pull of the ACL and the notch angle ($r = 0.73$, $p = 0.001$). The correlation between angle of pull and notch width at the articular margins of the femoral condyles approached significance. For females, there were no statistically significant correlations demonstrated. There was only one weak relationship shown - between angle of pull and notch width at the level of the popliteal recess ($r = 0.38$, $p = 0.116$).

The second part of this analysis correlates ACL angle of pull to notch and femoral condyle measurements obtained on coronal view MR images. Two statistically significant correlations were found for males. As with the correlation of angle of pull to axial notch measurements, the relationships between angle of pull and notch angle ($r = 0.72$, $p = 0.002$) and lateral wall angle ($r = 0.76$, $p = 0.001$) were strong. For females, two significant correlations were seen. The first was between the angle of pull and notch width at the level of the popliteal recess ($r = 0.67$, $p = 0.002$). The second was a positive correlation between angle of pull and lateral wall angle ($r = 0.52$, $p = 0.028$). Correlation between angle of pull and notch width at the articular margins of the femoral condyles approached significance ($r = 0.44$, $p = 0.071$).

Table 4.9 Correlation of Intercondylar Notch and Femoral Condyle Measurements to ACL Angle of Pull for Males and Females.

a. Axial Notch and Femoral Condyle Measurements

Males				Females			
Mean Axial Measurement (mm)		Pearson r	P Value	Mean Axial Measurement (mm)		Pearson r	P Value
M1-A	24.1	0.56 *	.023	M1-A	20.1	0.38	.116
M1-B	17.9	0.33	.205	M1-B	15.3	0.13	.616
M1-C	22.1	0.44	.084	M1-C	18.7	0.004	.988
M2	25.2	-0.15	.579	M2	22.9	0.20	.425
M3	44.6	0.73 **	.001	M3	43.5	0.28	.913
M4	23.7	0.52 *	.041	M4	25.1	-0.006	.982
M5	80.3	-0.05	.857	M5	70.2	0.07	.785
M6	75.1	0.02	.947	M6	66.0	0.002	.992
C	33.	-0.16	.559	C	30.5	0.23	.369

b. Coronal Notch and Femoral Condyle Measurements

Males				Females			
Mean Coronal Measurement (mm)		Pearson r	P Value	Mean Coronal Measurement (mm)		Pearson r	P Value
M1-A	21.8	0.32	.222	M1-A	18.0	0.67**	.002
M1-B	16.4	0.02	.949	M1-B	14.2	-0.02	.951
M1-C	19.3	0.22	.417	M1-C	16.1	0.44	.071
M2	22.0	-0.20	.465	M2	20.1	0.15	.547
M3	45.1	0.72 **	.002	M3	43.5	0.31	.209
M4	25.1	0.76 **	.001	M4	25.8	0.52 *	.028
M5	83.3	-0.04	.874	M5	73.9	0.03	.903
M6	74.5	0.01	.970	M6	66.1	0.12	.626
C	29.6	-0.29	.277	C	28.0	0.30	.226

* Indicates significance ($p<0.05$)
** Indicates significance ($p<0.01$)

The results of the analysis of the relationship between notch and femoral condyle size and ACL angle of pull for males and females combined are shown in Table 4.10. The first part of the analysis correlates notch size to the ACL angle of pull measurements obtained from the axial view MR images. Table 4.10a shows only one significant correlation - between the notch angle and the angle of pull of the ligament ($r = 0.351$, $p = 0.042$). The second part of the analysis correlates notch size to the angle of pull of the ACL measurements obtained from coronal view MR images. Table 4.10b shows two significant correlations. The first was between the notch angle and the angle of pull of the ACL ($r = 0.474$, $p = 0.005$). The second was between the lateral wall angle and the angle of pull of the ACL ($r = 0.604$, $p = 0.001$). No other significant correlations were observed. The table also shows a match in r values between the axial view ($r = -0.092$) and the coronal view ($r = -0.096$) for the greatest femoral bicondylar width.

Table 4.10 Correlation of Intercondylar Notch and Femoral Condyle Measurements to ACL Angle of Pull for Males and Females Combined.

a. Axial Notch and Femoral Condyle Measurements

Mean Axial Measurement (mm)		Pearson r	P value
M1-A	21.9	0.251	0.154
M1-B	16.5	0.131	0.457
M1-C	20.3	0.132	0.456
M2	23.9	-0.084	0.637
M3	44.0	0.351 *	0.042
M4	24.4	0.278	0.112
M5	75.0	-0.092	0.603
M6	70.3	-0.089	0.617
C	31.7	0.008	0.963

b. Coronal Notch and Femoral Condyle Measurements

Mean Coronal Measurement (mm)		Pearson r	P value
M1-A	19.8	0.271	0.122
M1-B	15.2	-0.065	0.716
M1-C	17.6	0.208	0.237
M2	20.9	0.066	0.710
M3	44.2	0.474 **	0.005
M4	25.4	0.604 **	0.001
M5	78.3	-0.096	0.588
M6	70.0	-0.052	0.769
C	28.8	-0.029	0.871

* Indicates significance (p<0.05)
** Indicates significance (p<0.01)

Prediction of Intercondylar Notch Size

A stepwise multiple linear regression was used to determine the ability to predict intercondylar notch size. Tables 4.11 and 4.13 summarize the results of the analysis. Table 4.11 reports the results of the analysis of the ability to predict axial notch size using other axial notch measurements, ACL size and angle of pull, height, body mass, and gender. For notch width at the level of the popliteal recess, 85.1% of the variation could be explained by knowing the notch width at the level of the articular margins of the medial and lateral femoral condyles, notch width at two-thirds notch height, ACL width, gender, and ACL angle of pull. Notch width at the articular margins of the medial and lateral femoral condyles and notch width at two-thirds notch height, gender, and ACL angle of pull were positive predictors of notch width at the level of the popliteal recess, while ACL width was a negative predictor, meaning that as notch width increased, ACL width decreased (standardized coefficient = -0.183). Notch width at two-thirds notch height was best predicted by notch width at the level of the popliteal recess and by notch depth ($R^2 = 0.519$). Both predictors were positive indicators of notch width. Notch width at the level of the articular margins of the medial and lateral femoral condyles was best predicted by notch width at the level of the popliteal recess, notch angle, and femoral bicondylar width at the popliteal recess ($R^2 = 0.861$). All predictors were positive indicators of notch width at the level of the articular margins of the medial and lateral femoral condyles. Notch height was best explained by notch depth and height ($R^2 = 0.430$). The analysis of the ability to predict notch angle indicated that 80.6% of the variation could be explained by notch width at the level of the popliteal recess, notch depth, and ACL angle of pull. Notch depth was shown to be a negative predictor of notch angle (standardized coefficient = -0.387). Lateral wall angle was best predicted by notch angle and notch height ($R^2 = 0.379$). Notch height was a negative predictor of lateral wall angle (standardized coefficient = -0.314). The analysis of the ability to predict the greatest femoral bicondylar width indicates that femoral bicondylar width at the popliteal recess, ACL length, subject height, and notch height were the best four predictors ($R^2 = 0.969$). Notch height was shown to be a negative predictor of femoral bicondylar width (standardized coefficient = -0.087). The greatest femoral bicondylar width and notch width at the articular margins of the medial and lateral femoral condyles were shown to account for 95.6% of the variation in femoral bicondylar width at the popliteal recess. Both predictors were positive indicators of bicondylar width. Finally, notch depth was best predicted by notch height and notch width at two-thirds notch height ($R^2 = 0.433$).

Table 4.11 Summary of Axial Stepwise Multiple Linear Regression Analysis

Dependent Variable	Model	Predictive Factors	R	R Square	P value
notch width at the level of the popliteal recess (M1-A)	5	notch width at the articular margins of the medial and lateral femoral condyles (M1-C), notch width at two-thirds notch height (M1-B), ACL width, gender, ACL angle of pull	0.923	0.851	0.001
notch width at two-thirds notch height (M1-B)	2	notch width at the level of the popliteal recess (M1-A), notch depth (C)	0.720	0.519	0.001
notch width at the articular margins of the medial and lateral femoral condyles (M1-C)	3	notch width at the level of the popliteal recess (M1-A), notch angle (M3), femoral bicondylar width at the level of the popliteal recess (M6)	0.928	0.861	0.001
notch height (M2)	2	notch depth (C), height	0.656	0.430	0.001
notch angle (M3)	3	notch width at the articular margins of the medial and lateral femoral condyles (M1-C), notch depth (C), ACL angle of pull	0.898	0.806	0.001
lateral wall angle (M4)	2	notch angle (M3), notch height (M2)	0.615	0.379	0.001
greatest femoral bicondylar width (M5)	4	femoral bicondylar width at the level of the popliteal recess (M6), ACL length, height, notch height (M2)	0.984	0.969	0.001
femoral bicondylar width at the level of the popliteal recess (M6)	2	greatest femoral bicondylar width (M5), notch width at the articular margins of the medial and lateral femoral condyles (M1-C)	0.978	0.956	0.001
notch depth (C)	2	notch height (M2), notch width at two-thirds notch height (M1-B)	0.658	0.433	0.001
ACL length	3	gender, ACL angle of pull, greatest femoral bicondylar width (M5)	0.865	0.748	0.001
ACL width	1	body mass	0.420	0.177	0.013
ACL angle of pull	3	notch angle (M3), ACL length, notch width at the level of the popliteal recess (M1-A)	0.597	0.356	0.004

An analysis was also performed to determine if the axial notch measurements had the same axial and coronal predictive factors. Table 4.12 shows the results of the analysis. For notch width at the level of the popliteal recess, there were two of the same axial and coronal predictive factors - gender and notch width at two-thirds notch height. No match was found for ACL width, notch angle, or ACL angle of pull. Notch width at two-thirds notch height had notch width at the level of the popliteal recess as a common axial and coronal predictive factor. No match was found for notch depth or notch height. Notch width at the articular margins of the medial and lateral femoral condyles had all three of the same axial and coronal predictive factors - notch width at the popliteal recess, notch angle, and femoral bicondylar width at the popliteal recess. Notch angle had one axial and coronal predictive factor the same - notch width at the articular margins of the medial and lateral femoral condyles. Lateral wall angle also had only one axial and coronal predictive factor the same - notch angle. For the greatest femoral bicondylar width, there were two common predictive factors - femoral bicondylar width at the level of the popliteal recess and ACL length. Finally, the greatest femoral bicondylar width was the only predictive factor that was the same for femoral bicondylar width at the level of the popliteal recess. Neither notch height or notch depth had any of the same axial and coronal predictive factors.

Table 4.12 Axial Measurements and Axial and Coronal Predictive Factors

Axial Notch Measurements	Axial Predictive Factors	Coronal Predictive Factors
notch width at the level of the popliteal recess (M1-A)	notch width at the articular margins of the medial and lateral femoral condyles (M1-C), notch width at two-thirds notch height (M1-B), ACL width, gender, ACL angle of pull	gender, notch angle (M3), notch width at two-thirds notch height (M1-B)
notch width at two-thirds notch height (M1-B)	notch width at the level of the popliteal recess (M1-A), notch depth (C)	notch width at the level of the popliteal recess (M1-A), notch height (M2)
notch width at the articular margins of the medial and lateral femoral condyles (M1-C)	notch width at the level of the popliteal recess (M1-A), notch angle (M3), femoral bicondylar width at the level of the popliteal recess (M6)	notch width at the level of the popliteal recess (M1-A), notch angle (M3), femoral bicondylar width at the level of the popliteal recess (M6)
notch height (M2)	notch depth (C), height	notch width at the level of the popliteal recess (M1-A)
notch angle (M3)	notch width at the articular margins of the medial and lateral femoral condyles (M1-C), notch depth (C), ACL angle of pull	notch width at the articular margins of the medial and lateral femoral condyles (M1-C), notch depth (C), height
lateral wall angle (M4)	notch angle (M3), notch height (M2)	notch angle (M3)
greatest femoral bicondylar width (M5)	femoral bicondylar width at the level of the popliteal recess (M6), ACL length, height, notch height (M2)	femoral bicondylar width at the level of the popliteal recess (M6), ACL length
femoral bicondylar width at the level of the popliteal recess (M6)	greatest femoral bicondylar width (M5), notch width at the articular margins of the medial and lateral femoral condyles (M1-C)	greatest femoral bicondylar width (M5)
notch depth (C)	notch height (M2), notch width at two-thirds notch height (M1-B)	greatest femoral bicondylar width (M5)

Table 4.13 reports the results of the analysis of the ability to predict coronal intercondylar notch size using other coronal notch measurements, ACL size and angle of pull, height, mass, and gender. Notch width at the level of the popliteal recess was best predicted by notch width at the articular margins of the medial and lateral femoral condyles, notch width at two-thirds notch height, ACL angle of pull, height, and gender ($R^2 = 0.832$). All predictors were positive indicators of notch width. Notch width at two-thirds notch height was positively predicted by gender and notch height ($R^2 = 0.556$).

Notch width at the articular margins of the medial and lateral femoral condyles was positively predicted by notch width at the popliteal recess and notch angle ($R^2 = 0.628$). Notch height was best predicted by notch depth and notch width at two-thirds notch height ($R^2 = 0.752$). Notch angle was positively predicted by lateral wall angle ($R^2 = 0.644$). The greatest femoral bicondylar width was positively predicted by femoral bicondylar width at the popliteal recess and ACL length ($R^2 = 0.948$). Femoral bicondylar width at the popliteal recess was shown to be best predicted by the greatest femoral bicondylar width ($R^2 = 0.939$). Finally, notch depth was best predicted by notch height and (weight) ($R^2 = 0.776$).

Tables 4.11 and 4.13 indicate several similarities between the axial and coronal views in the predictive factors for seven of the nine notch measurements. For notch width at the level of the popliteal recess, four factors, notch width at the popliteal recess, notch width at two-thirds notch height, gender, and ACL angle of pull, were found to be predictors of notch width at the popliteal recess on both the axial and coronal views. For notch width at the articular margins of the medial and lateral femoral condyles, notch width at the popliteal recess and notch angle were predictive factors on the axial view, and were also found to be predictive factors on the coronal view. For notch height, the only common predictive factor was notch depth. Notch angle was found to be a common predictor for lateral wall angle. For the greatest femoral bicondylar width, two predictive factors were found on both the axial and coronal views. First was the femoral bicondylar width at the popliteal recess, and second was ACL length. The greatest femoral bicondylar width was shown to be a predictive factor for the femoral bicondylar width at the popliteal recess on both the axial and coronal views. Finally, notch height was found to be a predictive factor for notch depth on both the axial and coronal views. No matches were found for either notch width at two-thirds notch height or notch height.

Table 4.13 Summary of Coronal Stepwise Multiple Linear Regression Analysis

Dependent Variable	Model	Predictive Factors	R	R Square	P value
notch width at the level of the popliteal recess (M1-A)	7	notch width at the articular margins of the medial and lateral femoral condyles (M1-C), notch width at two-thirds notch height (M1-B), ACL angle of pull, height, gender	0.912	0.832	0.001
notch width at two-thirds notch height (M1-B)	2	gender, notch height (M2)	0.745	0.556	0.001
notch width at the articular margins of the medial and lateral femoral condyles (M1-C)	2	notch width at the level of the popliteal recess (M1-A), notch angle (M3)	0.792	0.628	0.001
notch height (M2)	2	notch depth (C), notch width at two-thirds notch height (M1-B)	0.867	0.752	0.001
notch angle (M3)	1	lateral wall angle (M4)	0.803	0.644	0.001
lateral wall angle (M4)	2	notch angle (M3), ACL angle of pull	0.842	0.709	0.001
greatest femoral bicondylar width (M5)	2	femoral bicondylar width at the level of the popliteal recess (M6), ACL length, height	0.974	0.948	0.001
femoral bicondylar width at the level of the popliteal recess (M6)	1	greatest femoral bicondylar width (M5)	0.969	0.939	0.001
notch depth (C)	2	notch height (M2), mass	0.881	0.776	0.001
ACL length	3	gender, greatest femoral bicondylar width (M5), ACL angle of pull	0.872	0.760	0.001
ACL width	1	mass	0.420	0.177	0.013
ACL angle of pull	1	lateral wall angle (M4)	0.604	0.364	0.001

An analysis was also performed to determine if the coronal notch measurements had the same axial and coronal predictive factors. Table 4.14 shows the results of the analysis. Notch width at the level of the popliteal recess had three out of five of the same axial and coronal predictive factors - notch width at the articular margins of the medial and lateral femoral condyles, notch width at two-thirds notch height, and ACL angle of pull. Notch width at two-thirds notch height had only gender as a common axial and coronal predictive factor. Notch width at the articular margins of the medial and lateral femoral condyles had one axial and coronal predictive factor the same - notch width at the level of the popliteal recess. The greatest femoral bicondylar width had two of the same predictive factors - femoral bicondylar width at the level of the popliteal recess and ACL length. There was only one predictive factor for femoral bicondylar width at the level of the popliteal recess - the greatest femoral bicondylar width. It was both an axial and a coronal predictor of femoral bicondylar width. Finally, notch depth had only one axial and coronal predictive factor the same - mass. Notch height, notch angle, and lateral wall angle all had none of the same axial and coronal predictive factors.

Table 4.14 Coronal Measurements and Axial and Coronal Predictive Factors

Coronal Notch Measurements	Axial Predictive Factors	Coronal Predictive Factors
notch width at the level of the popliteal recess (M1-A)	greatest femoral bicondylar width (M5), notch width at two-thirds notch height (M1-B), notch height (M2), ACL angle of pull, notch width at the articular margins of the medial and lateral femoral condyles (M1-C)	notch width at the articular margins of the medial and lateral femoral condyles (M1-C), notch width at two-thirds notch height (M1-B), ACL angle of pull, height, gender
notch width at two-thirds notch height (M1-B)	gender	gender, notch height (M2)
notch width at the articular margins of the medial and lateral femoral condyles (M1-C)	notch width at the level of the popliteal recess (M1-A), ACL width	notch width at the level of the popliteal recess (M1-A), notch angle (M3)
notch height (M2)	height	notch depth (C), notch width at two-thirds notch height (M1-B)
notch angle (M3)	notch width at the level of the popliteal recess (M1-A), ACL length	lateral wall angle (M4)
lateral wall angle (M4)	ACL angle of pull	notch angle (M3), ACL angle of pull
greatest femoral bicondylar width (M5)	femoral bicondylar width at the level of the popliteal recess (M6), notch depth (C), ACL length	femoral bicondylar width at the level of the popliteal recess (M6), ACL length
femoral bicondylar width at the level of the popliteal recess (M6)	greatest femoral bicondylar width (M5)	greatest femoral bicondylar width (M5)
notch depth (C)	body mass	notch height (M2), body mass

Prediction of ACL Size

A stepwise multiple linear regression was used to determine the ability to predict ACL size and angle of pull. Tables 4.11 and 4.13 summarize the results of the analysis. Table 4.11 reports the results of the analysis of the ability to predict ACL size and angle of pull using axial notch measurements, ACL size and angle of pull, height, mass, and gender. For ACL length, the best predictors were gender, ACL angle of pull, and the greatest femoral bicondylar width with an R^2 value of 0.748. Gender and femoral bicondylar width were shown to be positive predictors of ACL length, while ACL angle of pull was a negative predictor of ACL length (standardized coefficient = -0.217), meaning that as the ACL increased in length, the ACL pulled at a flatter angle. ACL width was positively predicted by mass ($R^2 = 0.177$). For ACL angle of pull, the best predictors were notch angle, ACL length, and notch width at the level of the popliteal recess. Angle of pull and ACL length were again shown to relate negatively. As the angle of pull increased (or got steeper), the ACL length decreased.

Table 4.13 reports the results of the analysis of the ability to predict ACL size and angle of pull using coronal notch measurements, ACL size and angle of pull, height, mass, and gender. As was demonstrated on the axial view, the best predictors of ACL length were gender, the greatest femoral bicondylar width, and ACL angle of pull ($R^2 = 0.760$). Again, ACL angle of pull was shown to be a negative predictor of ACL length (standardized coefficient = -0.214). ACL width was again positively predicted by mass ($R^2 = 0.177$). For ACL angle of pull, the best predictor on the coronal view was lateral wall angle ($R^2 = 0.364$).

Tables 4.11 and 4.13 indicate that using both the axial and coronal view images, ACL length could be predicted using gender, ACL angle of pull, and the greatest femoral bicondylar width, while ACL width could be predicted using mass. ACL angle of pull could not be predicted based on the same predictive factors on the axial view as compared to the coronal view.

Intercondylar Notch and Femoral Condyle Size and Subject Size

The Pearson correlation coefficient (r) was used to describe the relationship between the size of the intercondylar notch and femoral condyles and the height and mass of subjects. The results are shown in Tables 4.15, 4.16, 4.17, and 4.18.

Table 4.15 shows the correlation between the mean intercondylar notch and femoral condyle measurements as measured on both axial and coronal view MR images and the height of the subjects. Table 4.15a indicates only one statistically significant correlation. This was found between the greatest medial to lateral width of the femoral condyles and the mean subject height for the female group ($r = 0.48$, $p = 0.042$). Correlations between mean height and notch height ($r = 0.46$, $p = 0.057$), notch angle ($r = -0.40$, $p = 0.100$), and notch depth ($r = 0.44$, $p = 0.068$) all approached significance. For the male group, no statistically significant correlations were found, however, correlations with notch height ($r = 0.49$, $p = 0.056$) and the greatest width of the femoral condyles ($r = 0.44$, $p = 0.088$) were close to significance.

When coronal notch measurements were correlated with subjects' height, four statistically significant relationships were found. For the male group, there were two positive correlations - between the subjects' mean height and notch width at the popliteal recess ($r = 0.51$, $p = 0.042$) and notch height ($r = 0.56$, $p = 0.023$). There was also a strong correlation between the mean subject height and notch depth ($r = 0.73$, $p = 0.001$). The female group showed a significant correlation between mean subject height and the greatest width of the femoral condyles ($r = 0.50$, $p = 0.035$). The remainder of the correlations for both the male and female groups were not statistically significant, with the relationships ranging from not significant to approaching significance.

Table 4.15 also indicates several close matches in correlations between the axial and coronal views. For the male group, the r value for notch width at two-thirds notch height (M1-B) is -0.03 on the axial view and -0.08 on the coronal view. For the greatest femoral bicondylar width (M5), the r value is 0.44 on the axial view and 0.38 on the coronal view. For the female group, the r value for the greatest femoral bicondylar width (M5) reaches significance at 0.48 ($p = 0.042$) on the axial view, and also reaches significance at 0.50 ($p = 0.035$) on the coronal view. For the bicondylar width at the popliteal recess (M6) and notch depth (C) on the axial view the r values are 0.41 and 0.44, respectively. On the coronal view, the r values are similar at 0.44 and 0.40, respectively.

Table 4.15 Correlation of Intercondylar Notch and Femoral Condyle Measurements to Height of Subjects

a. Axial Notch and Femoral Condyle Measurements

Males: Mean Axial Measurement (mm)		Pearson r	P Value	Females: Mean Axial Measurement (mm)		Pearson r	P Value
M1-A	24.1	-0.02	.943	M1-A	20.1	-0.08	.749
M1-B	17.9	-0.03	.920	M1-B	15.3	0.18	.470
M1-C	22.1	-0.03	.910	M1-C	18.7	-0.21	.413
M2	25.2	0.49	.056	M2	22.9	0.46	.057
M3	44.6	-0.03	.899	M3	43.5	-0.40	.100
M4	23.7	0.11	.674	M4	25.1	-0.23	.351
M5	80.3	0.44	.088	M5	70.2	0.48 *	.042
M6	75.1	0.27	.304	M6	66.0	0.41	.093
C	33.0	0.24	.376	C	30.5	0.44	.068

b. Coronal Notch and Femoral Condyle Measurements

Males: Mean Coronal Measurement (mm)		Pearson r	P Value	Females: Mean Coronal Measurement (mm)		Pearson r	P Value
M1-A	21.8	0.51 *	.042	M1-A	18.0	0.11	.677
M1-B	16.4	-0.08	.766	M1-B	14.2	-0.01	.972
M1-C	19.3	0.16	.560	M1-C	16.1	-0.14	.574
M2	22.0	0.56 *	.023	M2	20.1	0.28	.257
M3	45.1	-0.17	.523	M3	43.5	-0.08	.744
M4	25.1	0.03	.908	M4	25.8	0.001	.996
M5	83.3	0.38	.144	M5	73.9	0.50 *	.035
M6	74.5	0.35	.186	M6	66.1	0.44	.067
C	29.6	0.73 **	.001	C	28.0	0.40	.102

* Indicates significance ($p<0.05$)
** Indicates significance ($p<0.01$)

Table 4.16 reports the results of the analysis of the relationship between notch and femoral condyle size and subjects' height for males and females combined. Table 4.16 indicates six significant correlations. These were found between height and notch width at the popliteal recess ($r = 0.394$, $p = 0.021$), notch width at two-thirds notch height ($r = 0.375$, $p = 0.029$), notch height ($r = 0.558$, $p = 0.001$), the greatest width of the femoral condyles (r = 0.702, p = 0.001), width of the femoral condyles at the level of the popliteal recess (r = 0.643, p = 0.001), and notch depth (r = 0.539, p = 0.001) on the axial view. These same significant correlations were also found on the coronal view except for the notch width at two-thirds notch height (M1-B) which did not reach significance with an r value of 0.315.

Table 4.16 Correlation of Intercondylar Notch and Femoral Condyle Measurements to Height of Subjects for Males and Females Combined.

a. Axial Notch and Femoral Condyle Measurements

Mean Axial Measurement (mm)		Pearson r	P value
M1-A	21.9	0.394 *	0.021
M1-B	16.5	0.375 *	0.029
M1-C	20.3	0.214	0.224
M2	23.9	0.558 **	0.001
M3	44.0	-0.125	0.480
M4	24.4	-0.129	0.467
M5	75.0	0.702 **	0.001
M6	70.3	0.643 **	0.001
C	31.7	0.539 **	0.001

b. Coronal Notch and Femoral Condyle Measurements

Mean Coronal Measurement (mm)		Pearson r	P value
M1-A	19.8	0.588 **	0.001
M1-B	15.2	0.315	0.069
M1-C	17.6	0.312	0.073
M2	20.9	0.500 **	0.003
M3	44.2	-0.042	0.813
M4	25.4	-0.027	0.878
M5	78.3	0.694 **	0.001
M6	70.0	0.665 **	0.001
C	28.8	0.582 **	0.001

* Indicates significance ($p<0.05$)
** Indicates significance ($p<0.01$)

The results of the analysis of the relationship between notch and femoral condyle size and subjects' mass are reported in Table 4.17. Correlation of notch and femoral condyle measurements from axial view MR images with subjects' mass revealed only one statistically significant relationship. This was between the mean subjects' mass and the greatest width of the femoral condyles for males ($r = 0.56$, $p = 0.023$). The remaining correlations range from low to very low for both males and females.

Table 4.17b indicates two significant correlations. Both were found in the male group. The first was a moderate correlation between notch height and subjects' mass ($r = 0.52$, $p = 0.039$). The second was a strong correlation between subjects' mass and notch depth ($r = 0.81$, $p = 0.001$). For the males, correlation of mass with the following four measurements produced results that were close to significance: notch angle ($r = 0.48$, $p = 0.058$), lateral wall angle ($r = -0.49$, $p = 0.053$), greatest width of the femoral condyles ($r = 0.42$, $p = 0.104$), and width of the condyles at the level of the popliteal recess ($r = 0.41$, $p = 0.113$). The females had two results that were close to significance. These were the correlations between mass and the greatest width of the femoral condyles ($r = 0.40$, $p = 0.099$) and the width of the condyles at the level of the popliteal recess ($r = 0.43$, $p = 0.076$) in the coronal view.

Table 4.17 also reveals three correlations which are similar between the axial and coronal views. First is femoral bicondylar width at the level of the popliteal recess (M6). For the male group, the r value is 0.38 on the axial view and 0.41 on the coronal view. Fore the female group, the r value for the greatest femoral bicondylar width (M5) is 0.38 on the axial view and 0.40 on the coronal view. Also for the female group, the r value for notch depth (C) on the axial view is 0.34 and 0.36 on the coronal view.

Table 4.17 Correlation of Intercondylar Notch and Femoral Condyle Measurements to Mass of Subjects

a. Axial Notch and Femoral Condyle Measurements

Males: Mean Axial Measurement (mm)		Males: Pearson r	Males: P Value	Females: Mean Axial Measurement (mm)		Females: Pearson r	Females: P Value
M1-A	24.1	-0.13	.634	M1-A	20.1	-0.01	.958
M1-B	17.9	-0.23	.385	M1-B	15.3	0.41	.090
M1-C	22.1	-0.05	.861	M1-C	18.7	-0.08	.740
M2	25.2	0.34	.201	M2	22.9	0.35	.151
M3	44.6	-0.17	.538	M3	43.5	-0.18	.465
M4	23.7	0.11	.685	M4	25.1	-0.15	.550
M5	80.3	0.56 *	.023	M5	70.2	0.38	.118
M6	75.1	0.38	.145	M6	66.0	0.30	.227
C	33.0	0.06	.820	C	30.5	0.34	.163

b. Coronal Notch and Femoral Condyle Measurements

Males: Mean Coronal Measurement (mm)		Males: Pearson r	Males: P Value	Females: Mean Coronal Measurement (mm)		Females: Pearson r	Females: P Value
M1-A	21.8	0.20	.457	M1-A	18.0	0.31	.215
M1-B	16.4	0.05	.846	M1-B	14.2	-0.09	.718
M1-C	19.3	0.18	.513	M1-C	16.1	0.001	.997
M2	22.0	0.52 *	.039	M2	20.1	0.22	.376
M3	45.1	-0.48	.058	M3	43.5	0.05	.833
M4	25.1	-0.49	.053	M4	25.8	0.14	.575
M5	83.3	0.42	.104	M5	73.9	0.40	.099
M6	74.5	0.41	.113	M6	66.1	0.43	.076
C	29.6	0.81 **	.001	C	28.0	0.36	.136

* Indicates significance ($p<0.05$)
** Indicates significance ($p<0.01$)

Table 4.18 reports the results of the analysis of the relationship between notch and femoral condyle size and subjects' mass for males and females combined. Table 4.18 indicates three significant correlations on the axial view. These were found for notch height ($r = 0.407$, $p = 0.017$), the greatest femoral bicondylar width ($r = 0.495$, $p = 0.003$), and femoral bicondylar width at the level of the popliteal recess ($r = 0.428$, $p = 0.012$).

These correlations were also found to be significant on the coronal view. For notch height, the r value was 0.468 (p = 0.005), for the greatest femoral bicondylar width the r value was 0.463 (p = 0.006), and for the femoral bicondylar width at the popliteal recess the r value was 0.472 (p = 0.005).

Table 4.18 Correlation of Intercondylar Notch and Femoral Condyle Measurements to Mass of Subjects for Males and Females Combined

a. Axial Notch and Femoral Condyle Measurements

Mean Axial Measurement (mm)		Pearson r	P value
M1-A	21.9	0.144	0.417
M1-B	16.5	0.173	0.327
M1-C	20.3	0.090	0.612
M2	23.9	0.407 *	0.017
M3	44.0	-0.139	0.433
M4	24.4	-0.032	0.859
M5	75.0	0.495 **	0.003
M6	70.3	0.428 *	0.012
C	31.7	0.304	0.081

b. Coronal Notch and Femoral Condyle Measurements

Mean Coronal Measurement (mm)		Pearson r	P value
M1-A	19.8	0.366 *	0.034
M1-B	15.2	0.157	0.376
M1-C	17.6	0.237	0.178
M2	20.9	0.468 **	0.005
M3	44.2	-0.192	0.277
M4	25.4	-0.153	0.386
M5	78.3	0.463 **	0.006
M6	70.0	0.472 **	0.005
C	28.8	0.655 **	0.001

* Indicates significance ($p<0.05$)
** Indicates significance ($p<0.01$)

Anterior Cruciate Ligament Size and Subject Size

The relationship between the length, width, and angle of pull of the ACL and subjects' height and mass is indicated in Tables 4.19 and 4.20. Table 4.19 indicates that there was a positive correlation between the length of the ACL and mass for males. This correlation, however, did not quite reach significance (r = 0.49, p = 0.057). The remaining correlations were all non-significant.

There was a positive correlation between ACL width and subject height for males (r = 0.51, p = 0.044). This correlation was statistically significant. There were also positive correlations for both males and females between ACL width and subject mass which were not statistically significant (r = 0.45, p = 0.079; r = 0.41, p = 0.089), respectively.

Finally, there was one negative correlation for males - between angle of pull and mass. This correlation approached very close to significance (r = 0.49, p = 0.052). The remaining correlations indicated virtually non-existent relationships.

Table 4.20 shows the correlation of ACL size and angle of pull with subject height and mass for males and females combined. Three significant correlations are indicated. First was between ACL length and subject height (r = 0.539, p = 0.001). Second was between ACL length and subject mass (r = 0.423, p = 0.013), and third was between ACL width and subject mass (r = 0.420, p = 0.013).

Table 4.19 Correlation of ACL Size and Angle of Pull with Subject Height and Body Mass.

	Males r Value	P Value	Females r Value	P Value
Length: Height	0.28	.296	0.12	.633
Length : Mass	0.49	.057	0.19	.454
Width: Height	0.51 *	.044	0.07	.778
Width: Mass	0.45	.079	0.41	.089
Angle of Pull: Height	0.11	.684	0.04	.865
Angle of Pull: Mass	-0.49	.052	0.20	.424

* Indicates significance (p<0.05)
** Indicates significance (p<0.01)

Table 4.20 Correlation of ACL Size and Angle of Pull with Subject Height and Body Mass for Males and Females Combined.

	Males and Females r value	P value
Length : Height	0.539 **	0.001
Length : Mass	0.423 *	0.013
Width : Height	0.229	0.193
Width : Mass	0.420 *	0.013
Angle of Pull : Height	-0.014	0.938
Angle of Pull : Mass	-0.189	0.284

* Indicates significance ($p<0.05$)
** Indicates significance ($p<0.01$)

CHAPTER 5

DISCUSSION

Introduction

Research on anterior cruciate ligament injuries has been unable to provide a concrete explanation as to why females are tearing their ACLs at a reported rate of three to four times that of males (Arendt, et al., 1999). Many of the studies reviewed cite the reasons as multifactorial, with no one anatomical, biomechanical, or physiological element being the sole cause. These elements may include such extrinsic factors as muscular strength, the interaction between a shoe and the playing surface, skill and conditioning levels, and experience combined with intrinsic factors such as limb alignments, ligament laxity, ligament size, ligament strength, and variation in intercondylar notch size (Beck and Wildermuth, 1985; Hutchinson and Ireland, 1995; Arendt, 1994; Rochman, 1996).

The contribution of the intercondylar notch to this predisposition for injury is controversial. Prior to about 1994, it had received less attention than some of the other proposed factors. Since then interest in the role of the notch has increased. The intercondylar notch width and the ratio of notch width to the femoral bicondylar width - the notch width index have been studied using various imaging techniques and modalities (Anderson, et al., 1987; Good, et al., 1991; LaPrade and Burnett, 1994; Lund-Hanssen, et al., 1994; Schickendantz and Weiker, 1993; Shelbourne, et al., 1998; Shelbourne, et al., 1997; Souryal and Freeman, 1993; Souryal, et al., 1988; Teitz, et al., 1997; Ireland, et al., 2001). Notch width measurements have been obtained from x-rays, computed tomography scans, and magnetic resonance imaging. The NWI was calculated in several studies, in a variety of sample populations - from high school athletes, to sedentary men and women, to varsity athletes (LaPrade and Burnett, 1994; Ireland, Ballantyne, Little, and McClay, 2001; Souryal and Freeman, 1993). The focus of the majority of the literature was to compare the NWI in ACL injured and uninjured knees to determine if there was a relationship between notch width and the incidence of ACL tears. The reports agreed that there was a relationship between a narrow notch and ACL injuries for both athletes and general populations of males and females but do not extend their investigations further (Souryal and Freeman, 1993; Lund-Hanssen, et al., 1994; LaPrade and Burnett, 1994).

To further determine the importance of the intercondylar notch, recent studies are beginning to investigate the relationship between the size of the notch and the size of the ACL. Most of the recent research has examined the width of the notch and its relation to the width of the ligament (Davis, et al., 1999; Rizzo, Holler, and Bassett, 2001; Anderson, Dome, Gautam, Awh, and Rennirt, 2001; Staeubli, Adam, Becker, and Burgkart, 1999).

What has been poorly studied or, is absent as yet, is an examination of other parameters of the notch size - its height, depth, and its opening angles, and how these measurements relate to the size of the ACL - to its width, to its length, and to its angle of pull, and if a predictability of size exists.

Gender and Intercondylar Notch Size

Are there absolute differences in intercondylar notch size between males and females? According to the results of this study, all of the mean notch measurements on both axial and coronal MR images were absolutely larger in males than in females, with the exception of one (Table 4.2 and 4.3). The lateral wall angle of the notch was just slightly wider in females. This general trend was not unexpected as the male subjects were taller and heavier than the females. Why would the notch overall be larger in males? One argument that was presented was the size of males - they have larger bone structure and generally larger overall size (Teitz, Lind, and Sacks, 1997; Souryal and Freeman, 1993). Souryal and Freeman (1993) hypothesized that the notch becomes narrowed in females because of a large lateral femoral condyle. This has not been tested by any studies. The actual shape of the notch may vary between males and females cause the narrowing. Hutchinson and Ireland (1995) have described the male notch as being reverse "U" or "C-shaped", with the female notch appearing more "A-shaped".

The following notch and femoral condyle measurements were significantly larger for males: M1-A - the intercondylar notch width at the level of the popliteal recess; M1-B - notch width at two-thirds notch height; M1-C - notch width at the articular margins of the medial and lateral femoral condyles; M2 - notch height; M5 - the greatest medial to lateral width of the femoral condyles; M6 - width of the femoral condyles at the level of the popliteal recess; and C - notch depth. However, no significant differences were found for notch angle or lateral wall angle on both axial and coronal images, or for notch height and notch depth on coronal view images only.

There was little to no information on causative explanations for these findings. An approximately equal number of studies found significant and non-significant differences between notch size in males and females (Table 5.1). Statements of existing or non-existent differences were made, with theories sometimes suggested.

Table 5.1 Intercondylar Notch Size Compared Between Males and Females

Reference	Gender Differences
LaPrade and Burnett (1994)	No significant differences (NWI = 0.244 males, 0.238 females)
Shelbourne, et al. (1997)	Notch width significantly narrower in females (NW = 15.3 mm, bilateral group; 15.8 mm, unilateral group; 16.9 mm, control group for males; NW = 12.8 mm, bilateral group; 13.8 mm, unilateral group; 14.5 mm, control group for females)
Souryal and Freeman (1993)	NWI in females significantly less than that in males (NWI = 0.239 males, 0.217 females)
Souryal, Moore, and Evans (1988)	No significant differences (values not reported)
Teitz, Lind, and Sacks (1997)	No significant differences (NWI = 0.257 males, 0.243 females)
Davis, Shelbourne, and Klootwyk (1999)	Notch width significantly narrower in females (NW = 19.0 mm males, 16.2 mm females)
Anderson, Dome, Gautam, Awh, and Rennirt (2001)	Notch width (23.7 mm males, 20.5 mm females) and notch width at two-thirds notch height (18.7 mm males, 16.2 mm females) significantly narrower in females; no significant differences in NWI (0.311 males, 0.305 females)
Rizzo, Holler, and Bassett (2001)	No significant differences in notch width (NW = 20.19 mm males, 20.50 mm females)
Shelbourne, and Kerr (2001)	Notch width significantly narrower in females (NW = 17.1 mm males, 14.7 mm females)
Shelbourne, Davis, and Klootwyk (1998)	Notch width significantly narrower in females (NW = 15.9 mm males, 13.9 mm females)
Anderson, Lipscomb, Liudahl, and Addlestone (1987)	No significant differences (values not reported)

One explanation for these different findings was a difference in measurement techniques and different points of measurement. For example, Herzog, et al. (1994) chose to measure their notch width at the level of the popliteal recess with a line through the centre of the recess. Anderson, et al. (2001) chose to make this same measurement with a line through the inferior aspect of the recess. This discrepancy may produce different results.

Another explanation was presented by Anderson, et al. (2001). They described the difference in the accuracy of CT scans and MRI as compared to radiographs. They stated that radiographs allow only a two-dimensional representation of a three-dimensional structure. If this structure is the curved femoral condyle, precise identification of a point may be difficult since even a slight rotation of the image will change the appearance and shape of the structure.

A third explanation was proposed by Shelbourne, et al. (1998). This referred to the use of the NWI instead of the absolute width as a measure of notch width. The purpose of the NWI was to standardize for patient size - it assumes that notch width and femoral bicondylar width directly correlate. Shelbourne, et al. (1998) found that condyle width did increase with increased height for both sexes, but that notch width did not. This may have an effect on the significance of the results. As can be seen in Table 5.1, both significant and non-significant results were found in the studies that use the NWI, while significant results were found in the majority of studies that use the absolute measurement of notch width. This also makes it difficult to make comparisons between studies that use the NWI and those that do not.

A fourth possible explanation for these different findings may be the use of different sample sizes and different sample populations.

Size of the Anterior Cruciate Ligament

Descriptive information on the size of the ACL is noticeably lacking in the literature. One report measured a mean length of 27.5 mm in a group of 20 individuals ranging from 48-86 years of age, and a mean length of 26.9 mm in a group of 6, ranging from 16-26 years of age (Noyes and Grood, 1976). A second report recorded a mean length of 34.9 mm for males and 31.52 mm for females (Butler, et al., 1992). Ellison and Berg (1985) found the average length in an adult to be approximately 40 mm. The length of the ACL is important because of the effect on failure of the ligament. Longer ligaments will be less stiff and must be stretched further before failure (Butler, et al., 1978).

The results of this study revealed that the anterior cruciate ligament ranged in length from 36.1 mm to 43.3 mm for males, and from 31.5 mm to 42.0 mm for females. These values are slightly longer than those reported in previous studies. On average, the ACL in males was 5.3 cm longer than that of females. This difference in length was statistically significant.

The anterior cruciate ligament can vary widely in width. This study found an average width for males of 4.7 mm, and an average width for females of 4.7 mm. The difference was non-significant and these values were found to be smaller than those previously reported. This finding of non-significant differences is supported by the work of Muneta, et al. (1997) and Anderson, et al. (2001). Muneta, et al. (1997) reported no significant differences in ACL width between sexes when they examined 16 cadaver knees from Japanese people. The researchers found the male knees to have an average ACL width of 5.5 mm, and females an average of 5.3 mm. Anderson, et al. (2001) indicated that no significant differences in ACL width were demonstrated between males and females when they studied a group of 50 male and 50 female high school basketball players. The study found a mean ACL width of 5.6 mm for males and 4.75 mm for females.

Studies by Davis, Shelbourne, and Klootwyk (1999) and Rizzo, Holler, and Bassett (2001) disagreed with this finding. Davis, et al. (1999) found that there was a significant difference in ACL width in their study group of 124 subjects (57 females and 67 males). The mean ACL width for males was 7.1 mm, and 5.7 mm for females. Rizzo, et al. (2001) directly examined cadaver knees of 15 males and 11 females with a caliper and micrometer. In the males, the mean ACL width was 10.59 mm, and in the females, the mean ACL width was 8.09 mm. This difference was statistically significant.

There are several possible explanations for the differences in length and width of the ACL found between previous studies, and for the differences in length and width of the ACL in this study as compared to those found in previous studies. First is the analysis of different patient populations. Several studies have demonstrated differences in ACL length and width between populations of high school athletes (average of 16 years), adults (age 16-47), and cadaver knees (age 33-96) (Anderson, et al., 2001; Rizzo, et al., 2001; Staeubli, et al., 1999). Second is the accuracy of magnetic resonance imaging (MRI). Although, Herzog, et al. (1994) determined MRI to be highly accurate when comparing MR images to cadaver measurements, some variation is still possible. Third is the amount of flexion or extension in the knee joint. Increasing the amount of knee flexion increases the amount of slack on the ACL, whereas fully extending the knee tightens the ligament (Moore, 1999). As a result, making a measurement of a ligament that is in tension versus one that is slackened may produce different results as the point of measurement may become different even though it might appear to be the same. This was observed in previous studies. Rizzo, et al. (2001) measured the ACL with the knee in 90 degrees of flexion and found the ligament to be an average of 10.59 mm for males and an average of 8.09 mm for females, while Anderson, et al. (2001) and Staeubli, et al. (1999) positioned their knees in full extension and found the ACL to be approximately 3 to 5 mm narrower. The present study found the width of the ACL to be narrower than results reported in previous studies. This may be explained by measuring the width of the ACL with the knee in full extension (which tightens the ACL), and measuring the width at its narrowest point. With regard to ligament length, flexing the knee tends to add some slack, especially to the posterolateral band of the ACL (Ellison and Berg, 1985). Therefore, measuring the length of the ACL on a sagittal oblique MR image with the knee flexed may produce inaccurate results if the point of measurement becomes different. Since the entire ligament is taut in full extension (Moore, 1999), this would seem to be the position of choice. This position (full extension) was used to measure the ACL length in this study. A fourth possible explanation is the actual points of measurement of the length and width of the ACL. The bundles of the ACL have been shown to be of different lengths (Butler, et al., 1992). Use of one of these lengths in one comparison and then the other length in the same comparison may produce different results. This was standardized in the present study by defining the length as the measurement of the longest fibres. Similarly, with regard to the width of the ACL, the midsubstance of the ligament tends to be narrower than the proximal and distal attachments. Precisely where the ligament is measured along its length, and at what level of the notch it is measured (i.e. at the popliteal recess or at the anterior outlet) will determine the consistency of the measurement.

Angle of Pull of the Anterior Cruciate Ligament

There are no scientific studies that investigate the importance of the angle of pull of the ACL. The only mention of this angle is in a study by Reicher, et al. (1985). The investigators describe the ACL traveling at approximately 20 degrees anteromedially to the vertical axis, or in other words, at approximately a 20 degree angle as it courses through the knee from the tibia to the femur. This angle is formed between the line perpendicular to the line along the inferior articular margins of the medial and lateral femoral condyles as viewed on an axial view MR image and a line through the midsubstance of the ligament on the same axial image (Figure 14).

The results of this study demonstrated that, for both males and females, the ACL pulled at a slightly greater angle than that reported by Reicher, et al. (1985). For males, the mean angle was 25.6 degrees. For females, the mean was slightly greater, at 27.0 degrees. These values were not statistically different.

The ACL follows a complex course as it travels through the knee from the tibia to the femur. The variation in angle of pull of the ACL in the present study as compared to the work of Reicher, et al. (1985) may be explained by three possibilities. First is the amount of flexion or extension of the knee joint. The angle of pull of the ACL may change repeatedly as the knee moves through its entire range of motion. Further study is needed to confirm this notion. Secondly is the level of the measurements of the angle of pull within the knee joint. Reicher, et al. (1985) measured the angle of pull at 1.5 cm superior to the tibial plateau. Since the ACL does twist and turn through the knee joint, variation from this level will most certainly change the angle. Thirdly may be the wider pelvis in females. The wider hips create a larger Q-angle, increased femoral anteversion, and an increased genu valgum (Arendt, 1994; Hutchinson and Ireland, 1995; Rochman, 1996). Any or all of these factors may affect the way the ACL sits within the intercondylar notch. The angle of pull of the ACL is important because if the angle was either too acute (straight up) or too obtuse (flat), it might impact the ability of the ligament to withstand the rotational stresses or forces of the tibia on the femur.

In the present study, the angle of pull of the ACL appears the be best correlated with notch angle and lateral wall angle. These relationships were better in males than females. Specifically, strong correlations were found between the angle of pull as it relates to notch angle (M3) and lateral wall angle (M4). When male and female results are combined, a significant positive relationship between notch angle and ACL angle of pull is observed on both axial and coronal views ($r = 0.351$, $p = 0.042$ on axial, and $r = 0.474$, $p = 0.005$ on coronal). With regard to lateral wall angle, a significant relationship was shown on the coronal view ($r = 0.604$, $p = 0.001$) but was not observed on the axial view ($r = 0.278$). This indicates the tendency for the ACL to pull at a more obtuse or flatter angle when the notch has a larger opening angle and a larger lateral wall angle.

ACL Size and Notch Size

The literature investigating the relationship between ACL size and notch size indicates no general agreement as to whether or not the size of the ligament is related to the size of the notch. Muneta, et al. (1997) divided the ACL into three sections - the midsubstance, tibial insertion, and femoral insertion, and measured the sagittal length, and width of each section. The ratio of width to sagittal length and cross-sectional area were also calculated for each section. The notch width index (NWI) was also calculated for each knee. The only significant relationship was between NWI and the ratio of width to sagittal length of the tibial insertion. The hypothesis that a narrow notch contains a smaller ACL was not observed. The researchers suggested instead that the size of the notch and the size of the ligament were mismatched - that "normal" sized ACLs are found within small, narrow notches.

The conclusions made by Muneta, et al. (1997) were supported by the work of Anderson, et al. (2001). Using images obtained from MR images, measurements were obtained for femoral condyle width, notch width, notch width at two-thirds notch height, axial and anteroposterior widths of the ACL, and the area of the ACL. The results found non-significant correlations between ACL area and notch width for both males ($r = 0.0177$) and females ($r = 0.225$), and non-significant relationships between ACL area and notch width at two-thirds notch height for both males ($r = 0.138$) and females ($r = 0.30$). The investigators concluded that the size of the ACL cannot be predicted from the size of the intercondylar notch.

Results contradictory to this study were found by Davis, et al. (1999). In their study group of 124 subjects (67 males, 57 females), strong, statistically significant correlations were found between notch width and ACL width for both males ($r = 0.84$, $p<0.001$) and females ($r = 0.80$, $p<0.001$), as measured on coronal view MR images at the level of the popliteal recess. Based on these strong correlations, the conclusion was that femoral intercondylar notch width can be used to predict ACL width.

A slightly different approach was taken by Rizzo, et al. (2001). Cadaver knee specimens were obtained from 15 males and 11 females for study purposes. Direct measurements with a caliper and micrometer were made of the width of the ACL at its midsubstance and of the width of the intercondylar notch at the articular margins of the femoral condyles. The results indicated that the width of the ACL was significantly larger in males (10.59 mm) than in females (8.09 mm). Notch width measurements were shown to be larger in females (20.50 mm) than in males (20.19 mm), but this difference was not statistically significant. Lastly, a ratio of the width of the ligament to the width of the notch was calculated. A significant difference was found when this ratio was tested for male-female differences. The ratio was found to be significantly larger in males. In other words, if the notch of a male knee was of equal size to the notch of a female knee, this ratio predicts that the ACL in the female knee would be smaller.

Shelbourne, et al. (1998) observed that patients with narrow intercondylar notches were five times more likely to tear their ACLs than those patients with wider notches. To determine if ligament size had any effect on tear rate, each patient received reconstruction with a standard size 10 mm graft and were monitored for tear rate. The results showed the tear rate to be nearly equal. The researchers proposed that notch size reflects ligament size - specifically that a narrow notch should house a smaller ACL.

Staeubli, Adam, Becker, and Burgkart (1999) also noted a positive correlation ($r = .66$) between ACL width and notch width at the level of the cruciate ligament intersection on coronal oblique MR images, suggesting a moderate level of ability to predict ligament size.

The analysis of the relationship between the ACL and the size of the intercondylar notch in the present study did not produce consistent or clear cut results. Measurements showing strong correlations in males did not necessarily, and often did not show the same correlations in females. As well, a correlation between a ligament measurement and an axial notch measurement was not always found when the same ligament measurement was correlated with a coronal notch measurements. Further, notch measurements that correlated with the angle of pull of the ACL did not always correlate with the ACL length or width.

The majority of these inconsistencies seem to be related to the imaging on the axial plane at the level of the popliteal recess, versus the coronal plane at the level of the anterior outlet of the notch. Certainly if the notch is measured at a different level, the size will change. This may account for some of the variation in the correlations. The small sample size used in this study may also preclude the appearance of some of the correlations.

However, several trends can be observed from the data. In terms of significance, when males and females are analyzed separately, the intercondylar notch seems to be poorly related to the length of the ACL. Only the greatest width of the femoral condyle (M5) on the coronal image in males showed a significant correlation with ACL length ($r = 0.50$, $p = 0.048$). This measurement does approach very close to significance in males using an axial view image ($r = 0.47$, $p = 0.066$). This measurement also appears to be poorly related to ACL length in females. There also appears to be weak relationship between ACL length and lateral wall angle for males. This is the angle between the perpendicular line from the apex of the notch to the line connecting the inferior articular surface of the femoral condyles and the line connecting the apex of the notch to the articular margin of the lateral femoral condyle (Herzog, et al., 1994). In males, although the correlations did not reach significance, they are just under moderate and are negative ($r = 0.42$, $p = 0.107$ on axial, and $r = 0.40$, $p = 0.128$ on coronal), indicating that as the lateral wall angle gets larger, the ACL should get shorter, and vice versa. This relationship in females, however, was virtually non-existent. When the male and female results are combined several significant correlations are demonstrated. Notch width at the level of the popliteal recess ($r = 0.529$, $p = 0.001$ on axial, and $r = 0.603$, $p = 0.001$ on coronal), notch width at two-thirds notch height ($r = 0.546$, $p = 0.001$ on axial, and $r = 0.583$, $p = 0.001$ on coronal), and notch width at the articular margins of the medial and lateral femoral condyles ($r = 0.460$, $p = 0.006$ on axial, and $r = 0.515$, $p = 0.002$ on coronal) all show significant positive correlations on both the axial and coronal view images. Significant positive correlations were also found for the greatest femoral bicondylar width ($r = 0.768$, $p = 0.001$ on axial, and $r = 0.770$, $p = 0.001$ on coronal), and for the femoral bicondylar width at the level of the popliteal recess ($r = 0.715$, $p = 0.001$ on axial, and $r = 0.725$, $p = 0.001$ on coronal). Notch depth also showed a significant correlation with ACL length ($r = 0.385$, $p = 0.025$ on axial, and $r = 0.426$, $p = 0.012$ on coronal). As was demonstrated when the male and female results were analyzed separately, no significant correlations were found between notch angle and ACL length ($r = 0.088$ on axial, and $r = -0.128$ on coronal), or between lateral wall angle and ACL length ($r = -0.242$ on axial, and $r = -0.197$ on coronal). There have been no scientific studies which have examined the relationship between notch size and ACL length.

The findings of a strong correlation between ACL width and notch width by Davis, et al. (1999), Rizzo, et al. (2001), and Shelbourne, et al. (1998) were not observed in this study. For both males and females, notch width was found to be poorly related to ACL width. Four significant correlations were observed. The first was between ACL width and the greatest femoral bicondylar width on the axial view for the male group ($r =$

0.60, $p = 0.015$). This relationship did not hold up, however, for the female group or on the coronal view. The second correlation was between ACL width and notch height on the coronal view for males ($r = 0.52$, $p = 0.038$). Again, this relationship did not hold up for females or on the axial view. Third was a significant correlation between ACL width and notch depth on the coronal view for males. This relationship was also not found on the axial view or for females on the coronal view. No evidence of this relationship was found for males, or on the axial view for females.

When the male and female results were combined, no significant correlations with ACL width were found for any of the notch measurements. Further, the largest r value observed was 0.296, indicating in this study the virtual absence of a relationship.

Somewhat surprising was the observation that the coronal notch measurements seem to be more highly correlated with ACL size and angle of pull than the axial measurements. Overall, there were more correlations between coronal notch measurements and ACL measurements that were either statistically significant or close to significance. Stronger correlations were also seen when coronal notch measurements were used. One possible explanation for this finding is the variability of individual notch measurements. The axial notch measurements were found to be slightly more variable than the coronal. An individual, for example, with a very wide notch or a large notch angle might negate another individual with a very narrow notch or a very small notch angle, and could result in smaller correlations. Another possibility is that where the notch is actually measured (the level) actually gives you a different percentage of correlation of size.

This observation is not totally without support. Anderson, et al. (2001) used axial MR images to measure notch width and to calculate ACL area. The results showed very small correlations for both males ($r = 0.177$) and females ($r = 0.225$) while Davis, et al. (1999) used coronal MR images to measure notch width and ACL width and found strong correlations for both males ($r = 0.84$, $p<0.001$) and females ($r = 0.80$, $p<0.001$).

Prediction of Intercondylar Notch Size

No scientific studies have been performed to determine if there is a predictability of the size of anatomical structures. The primary focus of the recent literature has been an attempt to establish a correlation as opposed to a dependence relationship. However, several interesting observations can be made based on the analysis in the present study. With a general inspection, notch measurements on an axial view MR image appear to have many of the same predictive factors as notch measurements on a coronal view MR image (refer to Table 4.12). The maximum number or predictive factors in any given axial or coronal model was five, with the number of corresponding individual matches ranging from one to three. If groups of similar measurements are examined, one measure in that group frequently had another measure in that same group as a predictive factor. These relationships intuitively make good sense and appear to be true for the groups of similar measurements on the axial view and on the coronal view, as well as when cross comparisons were studied to determine if axial measures could predict coronal measures and if coronal measures could predict axial measures. For example, in the group of notch width measurements (notch width at the popliteal recess, notch width at two-thirds notch height, and notch width at the articular margins of the medial and lateral femoral condyles), notch width at the popliteal recess had notch width at two-thirds notch height as one of its predictive factors. As well, both notch width at two-thirds notch height and notch width at the medial and lateral margins of the femoral condyles, had notch width at the popliteal recess as a predictive factor. The strongest predictor of notch height was notch depth, while the strongest predictor of notch depth was notch height. The greatest femoral bicondylar width and the femoral bicondylar width at the popliteal recess also appear to be the best predictors of each other. Finally, notch angle appears to be a predictive factor for lateral wall angle, but lateral wall angle appears to only predict notch angle on the coronal view.

When individual models were examined, the most interesting was the model for axial notch width at the level of the popliteal recess (refer to Table 4.11). Notch width at the articular margins of the medial and lateral femoral condyles, notch width at two-thirds notch height, gender, and ACL angle of pull were all found to be positive predictors of notch width. Somewhat unexpected, however, was that ACL width was found to be a negative predictor of notch width, meaning that as notch width increased, ACL width decreased, and the reverse is also true - that as notch width decreased, ACL width increased. This disagrees with the work of Davis, et al. (1999) who found a strong positive correlation between ACL width and notch width.

Second were the models for femoral bicondylar width. Shelbourne, et al. (1998) stated in their study on the relationship between notch width and the incidence of ACL tears, that femoral bicondylar width increases with increasing height. The present study found that height was a poor predictor of femoral bicondylar width. Height does not appear in the list of predictive factors for coronal femoral bicondylar width, or when the axial measure was regressed against the coronal measures, or when the coronal measure was regressed against the axial measures. Height does appear in the list of predictive factors for axial femoral bicondylar width, but it ranked only third in a list of four.

Finally, caution must be exercised when attempting to draw conclusions from the present study wherever height or mass measurements are used since all heights and mass were based on self-report.

Prediction of ACL Size

Three interesting observations can be made in regard to the ability to predict ACL size from the size of the notch, height, mass, and gender. First is the prediction of ACL width. The only predictor reported was mass. The inclusion of mass makes good sense in terms of a heavier body requiring wider (and perhaps thicker and stronger) ligaments for the daily increased loads these ligaments must support. Again, caution is required as mass was based on self-report. Second is the relationship between ACL length and ACL angle of pull. The present study predicted that as ACL angle of pull decreased (or got flatter), ACL length increased. This might impact the ability to withstand the rotational forces of the femur on the tibia. Third is the ability to predict ACL length. Regardless of whether axial or coronal notch measurements were used, the predictive factors for ACL length remained the same - gender, the greatest femoral bicondylar width, and ACL angle of pull.

Notch Size and Body Size

This section is for illustration purposes only due to the self-report of subject height and body mass.

When examining the relationship between height and notch size, the literature tends to focus on the relationship between notch width and the subject's height. There is some conflict in the findings. Shelbourne, et al. (1998) found that when examining notch width in 714 patients (480 males and 234 females), and height was accounted for, females still had statistically significantly narrower notch widths than males ($p<0.01$), suggesting that females have narrower notches, independent of height. This work was followed up with a radiographic study by Shelbourne and Kerr (2001) which examined the knees of 315 males and 163 females. The results were different. Females of the same height as males had significantly narrower notches ($p<0.01$), and there were very low correlations between height and notch width for males ($r = 0.0019$) and females ($r = 0.1308$). Staeubli, et al. (1999) reported a correlation of .482 (non-significant) between notch width and height from their MRI analysis of 51 knees (26 males and 25 females grouped together). One possible explanation for this larger r value (0.482 versus 0.0019 and 0.1308) is the use of a different measurement tool (MRI versus x-ray) and imaging in a different plane. Staeubli, et al. (1999) obtained their notch width measurements from coronal oblique view MR images, whereas the x-ray studies used strictly anteroposterior views.

The present study found that when males and females are analyzed separately, height is poorly related to notch width. The majority of the "r" correlation values are very small, ranging from -0.01 to 0.18. The one exception was a significant correlation between coronal notch width at the popliteal recess (M1-A) and height for males ($r = 0.51$, $p = 0.042$). This correlation did not hold up, however, for females or when height was correlated to axial notch width at the popliteal recess (M1-A).

There is some evidence in the literature to suggest that height may be related to femoral condyle width (Shelbourne, et al., 1998; Shelbourne and Kerr, 2001). Significant correlation values of 0.57 (Shelbourne, et al., 1998), and 0.67 (Shelbourne, and Kerr, 2001) have been reported for males, and significant values of 0.54 (Shelbourne, et al., 1998) and 0.785 (Shelbourne and Kerr, 2001) have been reported for females. The present data support these findings for females only. "R" values of M5 - the greatest femoral bicondylar width - of $r = 0.44$ and $r = 0.38$ were found for males, and significant r values of $r = 0.48$ and $r = 0.50$ were found for females (Table 4.15).

When the male and female data are combined, there are several significant correlations between notch size and height. Strong, significant correlations were found for notch width at the popliteal recess ($r = 0.394$, $p = 0.021$ on axial, and $r = 0.588$, $p = 0.0001$ on coronal), notch height ($r = 0.558$, $p = 0.001$ on axial, and $r = 0.500$, $p = 0.003$ on coronal), the greatest femoral bicondylar width ($r = 0.702$, $p = 0.001$ on axial, and $r = 0.694$, $p = 0.001$ on coronal), femoral bicondylar width at the popliteal recess ($r = 0.643$, $p = 0.001$ on axial, and $r = 0.665$, $p = 0.001$ on coronal), and notch depth ($r = 0.539$, $p = 0.001$ on axial, and $r = 0.582$, $p = 0.001$ on coronal).

The relationships between height and the bicondylar width at the popliteal recess (M6) for females, notch height (M2), and notch depth (C) have not been supported by other investigations and require an investigation where actual height and body mass were measured.

When examining the relationship between body mass and notch size, current research is again focused on the correlation with notch width. Preliminary studies by Shelbourne, et al. (1998) and Shelbourne and Kerr (2001) indicate the absence of this relationship. Correlation values for both sexes ranged from -0.0311 to 0.170. Staeubli, et al. (1999) contradicted these findings with a significant correlation of 0.587. The coronal oblique MR imaging plane has not been used in other studies to obtain notch width measurements. Further study may be needed to determine if this plane can provide accurate notch measurements.

The results of this study tend to support the studies by Shelbourne in 1998 and 2001. No significant correlations were found between mass and any of the three notch width measurements for either males or females (Table 4.17), or when the data for males and females are combined (Table 4.18).

Just as there was evidence to suggest that height may be related to femoral condyle width, there is some evidence that bicondylar width might be related to body mass. On inspection of Table 4.17, only one correlation for M5 (the greatest femoral bicondylar width) and M6 (bicondylar width at the level of the popliteal recess) reached statistical significance at 0.56, four others approached significance at an approximate "r" value of 0.40. However, when male and female data are combined, the r values for the correlations of mass with both the greatest femoral bicondylar width ($r = 0.495$, $p = 0.003$ on axial, and $r = 0.463$, $p = 0.006$ on coronal) and the femoral bicondylar width at the level of the popliteal recess ($r = 0.428$, $p = 0.428$, $p = 0.012$ on axial, and $r = 0.472$, $p = 0.005$ on coronal) reached statistical significance on both the axial and coronal views.

Even stronger evidence for this relationship has been described. Shelbourne, et al. (1998) reported a moderate relationship between these variables, citing correlations for males and females of 0.514 and 0.511 respectively, while strong correlations were demonstrated in two current studies (Shelbourne, et al., 2001; Staeubli, et al., 1999), citing correlations ranging from 0.694 up to 0.821. The larger sample sizes used in these studies may provide an explanation for these stronger correlations.

These results must be interpreted with caution due to the self-report of subject height and body mass.

ACL Size and Body Size

This section is for illustrative purposes only. The results are limited due to the self-report of subject height and body mass.

No scientific studies have been performed to investigate the relationship between height and mass and the length and width of the ACL. Noyes and Grood (1976) suggested the idea of a scaling law - that ligament length would increase in proportion to body mass to the one-third power. The researchers determined that human ACL length could be estimated from the length of the ACL of a rhesus monkey using this scaling law.

This scaling law, however, has not been tested any further. A study using strictly human subjects would be useful to test the application of this proposed law. Rizzo, et al. (2001) did not address, but suggested that ACL size should be considered in relation to body mass and the related functional loads. Finally, Anderson, et al. (2001) noted a correlation between ACL area and height for males. The observation was made that taller males had larger ACLs ($p = 0.03$), but the same could not be said for females ($p = 0.82$).

Intuitively, one might expect based on general body size, that taller individuals should have longer ligaments. This was not observed in the present study when males and females were analyzed separately. In fact, this analysis showed height and mass to be poorly related to ACL length. No significant correlations were found between height or mass and ACL length for either males or females. The consistency in the height of the subjects may account for the low correlations. The difference in the heights of males was only 30 cm from the tallest to the shortest, and only 36 cm for females. These differences may not be enough for a correlation to appear. A study of a group of subjects all over six feet tall tested against a group of subjects all five feet tall would likely produce different results. When the data for males and females were combined, however, height ($r = 0.539$, $p = 0.001$) and mass ($r = 0.423$, $p = 0.013$) were shown to be significantly related to ACL length.

When examining the correlation between height and ACL width, this study found a significant relationship for males ($r = 0.51$, $p = 0.044$) but not for females ($r = 0.07$, $p = 0.778$). A non-significant correlation was also found for height and ACL width when the results for males and females were combined ($r = 0.229$). This may be a reflection of the generally greater body size of males. No other suggestion for this difference can be made at this time.

When examining the ability of subject mass to predict ACL width, no significant correlations were found for either males ($r = 0.45$, $p = 0.079$) or females ($r = 0.41$, $p = 0.089$). The results, however, were both close to significance and were similar for both sexes, and do in fact reach significance when the data for males and females are combined. It is my opinion that this is more than a coincidence - that ligament width is a reflection of the loads these tissues must support on a daily basis.

Type I and Type II Errors

There is a possibility of type I and type II errors happening in the present study. Type I errors are possible because of the finding of significance of notch measurements on one view (either axial or coronal) and not on the other. This may be due in part to the slightly greater variability of the measurement on one view. Type II errors are possible since 0.05 was selected as the level of significance. Out of 180 correlations, one out of every twenty must be due to chance. Type II errors are also a possibility due to the small sample size of the study.

CHAPTER 6

SUMMARY, CONCLUSIONS, RECOMMENDATIONS

Summary

The purposes of this study were to determine: if there was an absolute difference between male and female measurements of both the intercondylar notch and the anterior cruciate ligament, if there was a relationship between the size of the intercondylar notch and the size of the ACL, if there was a predictive value of the size of anatomical structures, and if there was a relationship between notch and ACL size and height and body mass. Eighteen females and sixteen males were recruited to participate in the study. Each subject had a magnetic resonance imaging scan of their knee. For each subject, the following measurements were made of the intercondylar notch on both axial and coronal view MR images: M1-A - the width of the notch at the level of the popliteal recess, M1-B - the width of the notch at two-thirds notch height, M1-C - the width of the notch at the articular margins of the femoral condyles, M2 - notch height, M3 - notch angle, M4 - lateral wall angle, M5 - the greatest femoral bicondylar width, M6 - bicondylar width at the level of the popliteal recess, and C - notch depth. For each subject, the length, width, and angle of pull of the ACL were also measured.

The data was analyzed using an analysis of variance to determine if there were statistically significant differences between the size of the notch and the size of the ACL in males as compared to females, a stepwise multiple linear regression to determine if there was a predictability of anatomical structures, and multiple correlations to determine if there was a relationship between the size of the notch and the size of the ACL and height and body mass.

From these analyses, the study found significant differences between males and females with regard to notch width at three levels, notch height, femoral bicondylar width at two levels, and notch depth on axial view MR images. Differences in notch height and notch depth disappeared when these measurements were repeated on coronal view MR images. No significant differences were found for notch angle or lateral wall angle on either the axial or coronal MR images.

The ACL was found to be significantly longer (absolute size) in males. No significant differences were found between males and females with regard to ACL width or angle of pull.

Notch and femoral condyle size were generally shown to be poorly related to ACL length and width when males and females were analyzed separately, but showed a significant correlation with ACL length when male and female results were combined. Notch angle and lateral wall angle showed a strongly correlated to the ACL angle of pull in males.

Intercondylar notch width was not correlated to ACL width but was found to be a negative predictor of ACL width. Axial intercondylar notch and femoral condyle measurements appeared to have many of the same predictive factors as coronal notch and femoral condyle measurements. The predictive factors for ACL length were the same, regardless of whether axial or coronal notch and femoral condyle measurements were used.

Conclusions

In conclusion, this study found that:

1. There were significant differences between males and females with regard to intercondylar notch width at the level of the popliteal recess, at two-thirds notch height, and at the articular margins of the femoral condyles.

2. There were significant differences between males and females with regard to intercondylar notch height, intercondylar notch depth, and femoral bicondylar width.

3. There were no significant differences between males and females with regard to notch angle or lateral wall angle.

4. The ACL was significantly longer in males as compared to females.

5. There was no significant difference in ACL width in males as compared to females.

6. Intercondylar notch and femoral condyle size was poorly related to ACL length when males and females were analyzed separately but showed a significant relationship when the results were combined.

7. Intercondylar notch size was poorly related to ACL width.

8. Intercondylar notch angle and lateral wall angle were shown to be strongly correlated to the angle of pull of the ACL in males.

9. Intercondylar notch width was not correlated to ACL width but was found to be a negative predictor of ACL width, i.e., as notch width increased, ACL width decreased, and as notch width decreased, ACL width increased.

10. Axial intercondylar notch and femoral condyle measurements appeared to have many of the same predictive factors as coronal notch and femoral condyle measurements. These relationships held true when cross comparisons were made to determine if axial measures could predict coronal measures, and to determine if coronal measures could predict axial measures.

11. The predictive factors for ACL length were the same, regardless of whether axial or coronal notch and femoral condyle measurements were used.

12. The increased incidence of ACL injuries in females as compared to males likely

cannot be solely attributed to the intercondylar notch. The difference in injury rate is most likely the result of a combination of intrinsic and extrinsic factors, and the person is placed in the high risk category if they have a certain number of these factors.

Recommendations

1. Future studies should use actual measures of height and body mass and should not rely on self-report by the subject.

2. Future studies should ensure proper screening of subjects. One subject presented for the imaging session with a previous history of a partial tear of the right anterior cruciate ligament. This had gone undisclosed through the screening process, and as a result the left knee of this subject was imaged. Although this doesn't appear to have affected the present data, the screening process should be addressed.

3. Future studies of this nature should be performed using a larger sample size. It is possible that the small sample size used in this study had some effect on the results.

4. Further investigations should continue to explore aspects of intercondylar notch size that the present study has just begun to address. These include: notch height and depth, and notch angle and lateral wall angle, and their relation to ACL injuries and their ability to predict notch size.

5. Future studies should continue to investigate the angle of pull of the ACL and its relation to ACL injuries and to notch size.

6. Future studies should continue to attempt to standardize measurement techniques for the notch and the ACL.

7. Future studies need to address the size of the ACL in relation to its strength of the ligament.

REFERENCES

Anderson, A.F., Dome, D.C., Gautam, S., Awh, M.H., Rennirt, G.W. (2001). Correlation of anthropometric measurements, strength, anterior cruciate ligament size, and intercondylar notch characteristics to sex differences in anterior cruciate ligament tear rates. The American Journal of Sports Medicine. 29(1), 58-65.

Anderson, A.F., Lipscomb, B., Liudahl, K.J., Addlestone, R.B. (1987). Analysis of the intercondylar notch by computed tomography. The American Journal of Sports Medicine. 15(6), 547-552.

Arendt, E.A. (1994). Orthopaedic issues for active and athletic women. Clinics in Sports Medicine. 13(2), 483-487.

Arendt, E.A., Agel, J., Dick, R. (1999). Anterior cruciate ligament injury patterns among collegiate men and women. Journal of Athletic Training. 34 (2), 86-92.

Arendt, E.A., Dick, R. (1995). Knee injury patterns among men and women in collegiate basketball and soccer. The American Journal of Sports Medicine. 23 (6), 694-701.

Arnheim, D.D. (1999). Modern Principles of Athletic Training. Times Mirror/Mosby College Publishing. St. Louis, Missouri.

Beck, J.L., Wildermuth, B.P. (1985). The female athlete's knee. Clinics in Sports Medicine. 4 (2), 345-366.

Boden, B., Dean, G., Feagin, J. (undated). Mechanisms of injury in the anterior cruciate ligament. Submitted for publication in the American Journal of Sports Medicine. In Delfico, A.J., and Garrett, W.E. (1998). Mechanisms of injury of the anterior cruciate ligament in soccer players. Clinics in Sports Medicine. 17 (4), 779-785.

Buckwalter, K.A., Pennes, D.R. (1990). Anterior cruciate ligament: oblique sagittal MR imaging. Radiology. 175, 276-277.

Butler, D.L., Grood, E.S., Noyes, F.R., Zernicke, R.F. (1978). Biomechanics of ligaments and tendons. Exercise and Sport Sciences Reviews. R. Hutton (ed.). The Franklin Institute Press.

Butler, D.L., Guan, Y., Kay, M.D., Cummings, J.F., Feder, S.M., Levy, M.S. (1992). Location-dependent variations in the material properties of the anterior cruciate ligament. Journal of Biomechanics. 25(5), 511-518.

Davis, J.A., Brewer, J. (1993). Applied physiology of female soccer players. Sports Medicine. 16, 180-189.

Davis, T.J., Shelbourne, K.D., Klootwyk, T.E. (1999). Correlation of the intercondylar notch width of the femur to the width of the anterior and posterior cruciate ligaments. Knee Surgery, Sports Traumatology, Arthroscopy. 7, 209-214.

Delfico, A.J., Garrett, W.E. (1998). Mechanisms of injury of the anterior cruciate ligament in soccer players. Clinics in Sports Medicine. 17(4), 779-785.

Do-Dai, D.D., Stracener, J.C., Youngberg, R.A. (1994). Oblique sagittal MRI of anterior cruciate ligament. Journal of Computer Assisted Tomography. 18(1), 160-162.

Dye, S.F., Cannon, W.D. (1993). Anatomy and biomechanics of the anterior cruciate ligament. Clinics in Sports Medicine. 7(4), 715-725.

Ellison, A.E., Berg, E.E. (1985). Embryology, anatomy, and function of the anterior cruciate ligament. Orthopedic Clinics of North America. 16, 3-14.

Feagin, J.A., Lambert, K.L. (1985). Mechanism of injury and pathology of anterior cruciate ligament injuries. Orthopedic Clinics of North America. 16(1), 41-45.

Fitzgerald, S.W., Remer, E.M., Friedman, H., Rogers, L.F., Hendrix, R.W., Schafer, M.F. (1993). MR evaluation of the anterior cruciate ligament: value of supplementing sagittal images with coronal and axial images. American Journal of Roentgenography. 160, 1233-1237.

Friedman, R.L., Jackson, D.W. (1996). Magnetic resonance imaging of the anterior cruciate ligament: current concepts. Orthopedics. 19(6), 525-532.

Gedgaudas-McClees, R.K., Torres, W.E. (1990). Essentials of Body Computed Tomography. W.B. Saunders Company. Philadelphia, Pennsylvania.

Good, L., Odensten, M., Gillquist, J. (1991). Intercondylar notch measurements with special reference to anterior cruciate ligament surgery. Clinical Orthopaedics and Related Research. 263, 185-189.

Hassard, T.H. (1991). Understanding Biostatistics. Mosby-Year Book, Inc. St. Louis, Missouri.

Herzog, R.J., Silliman, J.F., Hutton, K., Rodkey, W.G., Steadman, R. (1994). Measurements of the intercondylar notch by plain film radiography and magnetic resonance imaging. The American Journal of Sports Medicine. 22(2), 204-210.

Houseworth, S.W., Mauro, V.J., Mellon, B.A., Kieffer, D.A. (1987). The intercondylar notch in acute tears of the anterior cruciate ligament: a computer graphics study. The American Journal of Sports Medicine. 15(3), 221-224.

Huston, L.J., Greenfield, M.L.V.H., Wojtys, E.M. (2000). Anterior cruciate ligament injuries in the female athlete. Clinical Orthopaedics and Related Research. 372, 50-63.

Huston, L.J., Wojtys, E.M. (1996). Neuromuscular performance characteristics in elite female athletes. The American Journal of Sports Medicine. 24(4), 427-436.

Hutchinson, M.R., Ireland, M.L. (1995). Knee injuries in female athletes. Sports Medicine. 19(4), 288-302.

Insall, J. (1979). Chondromalacia patella: patellar malalignment syndromes. Orthopedic Clinics in North America. 10, 117-125.

Ireland, M.L., Ballantyne, B.T., Little, K., McClay, IS. (2001). A radiographic analysis of the relationship between the size and shape of the intercondylar notch and anterior cruciate ligament injury. Knee Surgery Sports Traumatology Arthroscopy. 9(4), 200-205.

Janssen, I., Heymsfield, S.B., Wang, Z., Ross, R. (2000). Skeletal muscle mass and distribution in 468 men and women aged 18-88 yr. Journal of Applied Physiology. 89, 81-88.

Kennedy, J.C., Hawkins, R.J., Willis, R.B., Danylchuk, K.D. (1976). Tension studies of human knee ligaments. The Journal of Bone and Joint Surgery. 58-A(3), 350-355.

Kieffer, D.A., Curnow, R.J., Southwell, R.B. (1984). Anterior cruciate ligament arthroplasty. The American Journal of Sports Medicine. 12, 301-312.

Kirkendall, D.T., Garrett, W.E. (2000). The anterior cruciate ligament enigma: injury mechanisms and prevention. Clinical Orthopaedics and Related Research. 372, 64-68.

Kwan, M.K., Lin, T.H-C., Woo, S.L-Y. (1993). On the viscoelastic properties of the anteromedial bundle of the anterior cruciate ligament. Journal of Biomechanics. 26(4/5), 447-452.

LaPrade, R.F., Burnett, Q.M. (1994). Femoral intercondylar notch stenosis and correlation to anterior cruciate ligament injuries. A prospective study. The American Journal of Sports Medicine. 22(2), 198-203.

Levin, S. (1992). ACL reconstruction: the best treatment option? The Physician and Sportsmedicine. 20(6), 151-161.

Loudon, J.K., Jenkins, W., Loudon, K.L. (1996). The relationship between static posture and acl injury in female athletes. Journal of Orthopedics and Sports Physical Therapy. 24(2), 91-97.

Lund-Hanssen, H., Gannon, J., Engebretsen, L., Holen, K.J. (1994). Intercondylar notch width and the risk for anterior cruciate ligament rupture. ACTA Orthopedics Scandanavia. 65(5), 529-532.

Magee, D.J. (1992). Orthopedic Physical Assessment. W.B. Saunders Company. Philadelphia Pennsylvania.

McCallum, J. (1995). Out of joint. Sports Illustrated. February 13, 44-53.

Miller, A.E.J., MacDougall, J.D., Tarnopolsky, M.A., Sale, D.G. (1993). Gender differences in strength and muscle fiber characteristics. European Journal of Applied Physiology. 66, 254-262.

Moore, K.L., Dalley, A.F. (1999). Clinically Oriented Anatomy. Fourth Edition. Baltimore: Lippincott, Williams and Wilkins.

Muneta, T., Takakuda, K., Yamamoto, H. (1997). Intercondylar notch width and its relation to the configuration and cross-sectional area of the anterior cruciate ligament: a cadaveric knee study. The American Journal of Sports Medicine. 25(1), 69-72.

Nordin, M., Frankel, V.H. (1989). Basic Biomechanics of the Musculoskeletal System. Lea and Febiger. Malvern, Pennsylvania.

Noyes, F.R., Grood, E.S. (1976). The strength of the anterior cruciate ligament in humans and rhesus monkeys. Journal of Bone and Joint Surgery. 58(A), 1074-1082.

Powers, J.A. (1979). Characteristic features of injuries in the knee in women. Clinical Orthopaedics and Related Research. 143, 120-124.

Reicher, M.A., Rauschning, W., Goid, R.H., Bassett, L.W., Lufkin, R.B., Glen, W. (1985). High-resolution magnetic resonance imaging of the knee joint: normal anatomy. American Journal of Roentgenography. 145, 895-902.

Rizzo, M., Holler, S.B., Bassett, F.H. (2001). Comparison of males' and females' ratios of anterior cruciate-ligament width to femoral-intercondylar-notch width: a cadaveric study. American Journal of Orthopedics. 30(8), 660-664.

Rochman, S. (1996). Gender inequity. Training and Conditioning. 6(5), 11-20.

Schickendantz, M.S., Weiker, G.G. (1993). The predictive value of radiographs in the evaluation of unilateral and bilateral anterior cruciate ligament injuries. The American Journal of Sports Medicine. 21(1), 110-113.

Shambaugh, J.P., Klein, A., Herbert, J.H. (1991). Structural measures as predictors of injury in basketball players. Medicine and Science in Sports and Exercise. 23, 522-527.

Shelbourne, K.D., Davis, T.J., Klootwyk, T.E. (1998). The relationship between intercondylar notch width of the femur and the incidence of anterior cruciate ligament tears: a prospective study. The American Journal of Sports Medicine. 26(3), 402-408.

Shelbourne, K.D., Facibene, W.A., Hunt, J.J. (1997). Radiographic and intraoperative intercondylar notch width measurements in men and women with unilateral and bilateral anterior cruciate ligament tears. Knee Surgery Sports Traumatology Arthroscopy. 5(4), 229-233.

Shelbourne, K.D., Kerr, B. (2001). The relationship of femoral intercondylar notch width to height, weight, and sex in patients with intact anterior cruciate ligaments. The American Journal of Knee Surgery. 14(2), 92-96.

Souryal, T.O., Freeman, T.R. (1993). Intercondylar notch size and anterior cruciate ligament injuries in athletes. A prospective study. The American Journal of Sports Medicine. 21(4), 535-539.

Souryal, T.O., Moore, H.A., Evans, J.P. (1988). Bilaterality in anterior cruciate ligament injuries. Associated intercondylar notch stenosis. The American Journal of Sports Medicine. 16(5), 449-454.

Staeubli, H-U., Adam, O., Becker, W., Burgkart, R. (1999). Anterior cruciate ligament and intercondylar notch in the coronal oblique plane: anatomy complemented by magnetic resonance imaging in cruciate ligament-intact knee. The Journal of Arthroscopic and Related Surgery. 15(4), 349-359.

Steadman, J.R., Rodkey, W.G. (1993). Role of primary anterior cruciate ligament repair with or without augmentation. Clinics in Sports Medicine. 12(4), 685-695.

Stoller, D.W. (1997). Magnetic Resonance Imaging in Orthopaedics and Sports Medicine. Lippincott-Raven Publishers.

Teitz, C.C., Lind, B.K., Sacks, B.M. (1997). Symmetry of the femoral notch width index. The American Journal of Sports Medicine. 25(5), 687-690.

Wada, M., Tatsuo, H., Baba, H., Asamoto, K., Nojyo, Y. (1999). Femoral intercondylar notch measurements in osteoarthritic knees. Rheumatology. 38, 554-558.

Appendix A

National Research Council
Project Approval Letter

National Research Council Canada | Conseil national de recherches Canada

Institute for Biodiagnostics | L'Institut du biodiagnostic

Winnipeg, Canada
R3B 1Y6

NRC · CNRC

MEMORANDUM

Date February 15, 2000

To Management Committee Members
George Webster, Chair Research Ethics Board
Patrick Stroman, Principal Investigator

From Valery Kupriyanov
Chair, Project Selection Committee

Re PSC99.30: The relationship between intercondylar notch dimensions and anterior cruciate ligament (ACL) size. (REB2000-7)

In this proposal MRI will be used to investigate the relationship between the size of the intercondylar notch and the size of the anterior cruciate ligament in both males and females. The Institute for Biodiagnostics' Project Selection Committee, comprised of four internal members, has reviewed the above mentioned project proposal. The correspondence between PSC and the PI is attached.

This project is a collaboration between IBD and both the Universities of Manitoba and Winnipeg. It is estimated at a total cost of approximately $24,000.00. IBD expenditures totaling $15,000 are comprised of personnel $4,000, use of equipment $10,000, and operating expenditures $1,000. Additionally, external partner contributions are estimated at $9,332 (personnel time).

The PSC finds that the project has scientific merit and validity and recommends that IBD's Management Committee approve the project.

Should you have any questions, or require more information, please contact me.

Prepared by: Rena Papadimitropoulos

VK

Encl.: PSC questions and PI's responses
Revised proposal submission.

cc: Valerie Strevens

Appendix B

Letter to Prospective Participants

Letter to Prospective Participants

Date

Dear Prospective Participant:

I enclose information about a Magnetic Resonance (MR) Imaging research study being performed by researchers from the Institute for Biodiagnostics (IBD) of the National Research Council of Canada (NRC). This study is called "The Relationship Between Intercondylar Notch Size and the Size of the Anterior Cruciate Ligament (ACL) in Males and Females" and will take place at the Health Sciences Centre MRI facility.

Please

1. Read the enclosed material. If this does not answer all your questions, please feel free to call us.

2. Carefully review the list of medical conditions that might exclude you from this study. This is mainly for your safety. If you have any questions or concerns, we will be glad to help you address them.

3. The "Magnetic Resonance Screening Form" must be completed before you can participate in the study. A list of screening physicians has been enclosed or you may have your own physician complete this form. The physician may direct the invoice to me. NRC will pay a maximum of $22.00 for this consultation.

4. Please allow yourself at least 24 hours after reading the information in this package before scheduling an appointment for this study. When you wish to participate in this study, please call me to arrange a date and time.

If you have any questions or concerns, please telephone me at 984-2433 and I will either answer your questions directly or make a referral to an appropriate member of the research team.

Sincerely,

Valerie Strevens, PhD
Human Studies Co-ordinator

Appendix C

Poster Advertisement for Subjects

RESEARCH SUBJECTS REQUIRED

Would you like to volunteer as a research subject
for Magnetic Resonance Imaging (MRI) studies of the knee?

If you are:

- age 18 to 30
- in excellent health
- eligible to have an MRI scan (we will determine this)

you could participate in a research study run by investigators from the National Research Council Institute for Biodiagnostics, the University of Manitoba and the University of Winnipeg.

Volunteers will have an MRI scan done. Studies take 2 ½ hours at the Health Sciences Centre MRI facility.

Like more information?- call
Valerie - 984-2433 or Barbara - 984-6975
Institute for Biodiagnostics, National Research Council
435 Ellice Avenue, Winnipeg

Appendix D

Research Study Summary

Research Study Summary

WHAT IS THE RESEARCH ABOUT?

At the lower end of the thigh bone (the femur) is a notch known as the intercondylar notch. This notch can be different sizes and shapes. In males, the notch is usually larger and shaped like an upside down U. In females, the notch tends to be smaller and A shaped.

The anterior cruciate ligament (ACL) runs through the centre of this notch. This ligament prevents the knee from hyperextending and prevents the lower leg bone from sliding forward on the thigh bone, i.e. that feeling like the knee is "giving out".

If the notch is smaller or narrower, perhaps the ACL is smaller and therefore weaker. Little has been done, however, to examine this idea.

The purpose of this study is to see if there is a relationship between the size of the notch and the size of the anterior cruciate ligament in females as compared to males.

To try to answer this question, magnetic resonance imaging (MRI) will be used. MRI uses a strong magnetic field and radiofrequency waves and it produces very clear, three-dimensional images. The images will be used to measure the dimensions of the notch and the ligament. The results will be analyzed using statistics to determine if there is in fact a relationship between notch size and ligament size.

AM I ELIGIBLE TO PARTICIPATE?

To participate in this study, you must be in good health, 17 to 30 years of age, have no previous injury to the anterior cruciate ligament, posterior cruciate ligament, medial or lateral collateral ligaments, or either meniscus. You also must not have had any previous knee surgery. Screening by a physician is a requirement to participate. If you have been screened previously for one of our other MR studies, you may not need to have another form completed (Please check with the Human Studies Co-ordinator at 984-2433).

If any of the following applies to you, you may not participate in the study:

You have metal objects inside your body. MRI may be dangerous for anyone with metal implants or metal objects inside their body.
You, in the opinion of the screening physician or investigators, have a medical condition that could be made worse by any stress associated with participation in a research protocol. These conditions include heart and circulatory problems, seizure disorders, anxiety disorders, and mental disorders.
You have claustrophobia.
You are or may be pregnant.
You have had anterior cruciate ligament injuries or reconstructions.
You have had injuries to the posterior cruciate ligament, medial or lateral collateral ligaments, or either meniscus.
You weigh more than 350 lb.

WHAT WILL I HAVE TO DO?

The study will involve one visit to the Health Sciences Centre MRI unit when you will have a Magnetic Resonance (MR) scan of your knee. The scan itself will take about 90 minutes, but allow a total of 2 1/2 hours for the visit. You will be asked various questions before your appointment to make sure that there are no metal objects in your body, so that it is safe for you to have an MRI scan done. Please call the Human Studies Co-ordinator at 984-2433 if you would like more information about the study or if you would like to make an appointment to participate in the study.
At your appointment for the MR scan, an investigator will go through the Screening Form with you, give you information about the study and show you the MRI system (see the picture).
You should make sure that all your questions are answered and you agree to participate in the study before signing the consent form.

Before entering the magnet room, you will be asked to change into clothing which does not contain metal. You have a choice of wearing your own clothing, if it is metal-free (e.g., jogging suit) or the hospital gowns that we can provide.

For the MRI scan, you will be positioned comfortably on your back and provided with soft earplugs to reduce the noise from the MRI scanner (the sound it produces is a loud knocking noise). The knee to be imaged will be
placed inside a special MR coil which is shaped like a hollow cylinder (roughly 15 cm in diameter) with separate top and bottom halves. The top half will be taken off so that you can lie your knee inside the coil, and foam padding will be placed around your knee for comfort and to keep your knee from moving. The top half of the coil will then be latched in place, securing your knee. You will then be slid into the large, tunnel-shaped magnet, feet first, until your knee is at the center of the magnet. Once your knee is at the center, your head will be near the open end of the magnet, or possibly outside the magnet depending on your height. The magnet at the Health Sciences Centre has a field-strength of 1.5T (similar to most hospital MRI scanners). The tunnel is 60 cm (about 2 feet) across and is open at both ends.
During the scan, the MR operator will be in constant communication with you through a two-way intercom. At times you will be asked to remain very still so that the images will be sharp. After we have obtained images with your knee lying straight, the operator will enter the room to position your knee in a flexed position and images will be repeated.
After the scan has been completed and you have left the magnet room, we will ask you to fill out a questionnaire about how the study went for you.

IS THE STUDY CONFIDENTIAL?

Normally, only people directly involved with the research procedure are allowed in the study area. However, as this is a clinical facility, people not involved in the study may occasionally require access. All staff at the Health Sciences Centre are required to keep health information confidential, in accordance with the Health Information Act of Manitoba.
Information gathered in this research may be published or presented in public forums; however your name will not be used or revealed. Medical records that contain your identity will be treated as confidential in accordance with the Personal Health Information Act of Manitoba. All data obtained during your scan will be stored with an alpha-numerical code instead of your name. Only your file, which is kept securely in the Human Studies Coordinator's office, will have information which relates your name to the code.) Despite efforts to keep your personal information confidential, absolute confidentiality cannot be guaranteed. Organizations that may inspect and / or copy your research results for quality assurance and data analysis include groups such as the National Research Council Research Ethics Board and the University of Manitoba Nursing/Education Research Ethics Board.

WHAT ARE THE POSSIBLE HARMS OR BENEFITS?

MRI may be dangerous for anyone with metal inside their body. Some metal objects may move or heat up due to the magnetic force and radiofrequency waves used for MRI. We will screen you to make sure that it is safe for you to participate. You must tell us if you have had surgery, as metal may be left in your body after certain types of surgery. Please consider if you have any of the following:
Previous Surgery, such as:
Surgery involving metal, such as: clips, rods, screws, pins, wires.
Heart pacemaker
Implanted electrodes, pumps or electrical devices
Cochlear (inner ear) implants
Intraocular lens (eye) implants (Cataract lens allowed)
Any metallic foreign body, shrapnel or bullet (Have you have ever been a grinder, metal worker, welder, wounded during military service, etc.?)
Intrauterine contraceptive device (IUD) or contraceptive diaphragm
Dental work held in place by magnets
Non-removable dental braces and retainers

Tattooed eyeliner
Some tattoos (if you have tattoos, please discuss with the Human Studies Co-ordinator)
Non-removable metal jewellery (body piercing)
MRI is completely painless, but some people have felt minor, transient discomforts during MRI scans (e.g. dizziness, lightheadedness or a feeling of continued motion after being moved into the magnetic field) which usually subside within a few minutes. In rare cases, the dizziness progressed to the point of nausea, but subsided quickly outside the magnetic field. Some people may have a feeling of claustrophobia while they are in the magnet, and in extremely rare cases this feeling seems to have triggered a more persistent claustrophobia. Please let us know immediately if you experience claustrophobia (or any other discomforts), and we will discontinue the study.
No long-term adverse effects of MRI have been reported. We would contact you if any new risks are discovered. Please contact us or ask your physician to contact us if you experience any effects that you feel may be a result of your participation in the study.
Before you enter the magnet room, we will ask you to remove all metal objects, such as keys, coins, since they could be attracted to the MRI instrument with great force. If a metal object hit anyone in the way, it could cause serious injury.

This is a research study so you will not personally benefit by participating in this study.

WHAT ELSE SHOULD I KNOW?

You have the right to withdraw from the research study at any time and for any reason. The investigators reserve the right to end your participation for any reason.
We will give you $25 to cover any expenses you incur to participate in this research study. You may also request a copy of some of the images. Although this is not a diagnostic scan and any images obtained are for research purposes only, it is possible that the MR scan may disclose an unknown abnormality. In this event, a medical imaging specialist will review the images and we would send a report to your physician.
Please contact us if you would like any more information about the study. Please let us know if you would like copies of any published scientific reports about the research project.

HOW CAN I GET MORE INFORMATION?

The following people may be contacted for additional information:

Dr. Glen Bergeron, PhD	(204) 786-9190
Dr. Patrick Stroman, PhD	(204) 984-6973
Kelly Klassen	( )

Dr. Valerie Strevens, PhD (Human Studies co-ordinator) (204) 984- 2433

For questions about your rights as a research subject, you may contact:

Ms. Brigitte Delannoy, National Research Council Winnipeg Research Ethics Board, phone 984-4533.

This study has been approved by the University of Manitoba Education/Nursing Research Ethics Board and any complaint regarding a procedure may be reported to the Human Ethics Secretariat (474-7122).

Appendix E

Physician Screening Form

MAGNETIC RESONANCE SCREENING FORM

This questionnaire is intended to confirm eligibility of potential research subjects and to identify factors which could make participation in an MRI study hazardous. For your safety, please complete the following screening form with your physician:

Research Subject's Name: (please print) ______________________________

Date of birth (D/M/Y): ____________ Male ( ) Female ( )

Weight _____ lb. or _____ kg. Height Ft ____ in ___ or _____ cm

Please refer to the Exclusion Criteria for MR studies and the examples provided.

SECTION A

If you have any metal in your body as a result of surgery, you will NOT be eligible to participate in our MRI research studies

		YES	NO
A 1	Have you ever had any surgery?	( )	( )

If yes, please list surgeries and approximate dates:

____

____

	YES	NO
To the best of your knowledge and your physician's knowledge, did any surgery require any metal to remain in your body?	( )	( )

(If there is doubt, the Human Studies Co-ordinator will ask your permission to check your medical records)

SECTION B

If you answer YES to one or more of the questions in Section B, you will NOT be eligible to participate in our MRI research studies.

B1 Do you have any of the following?	YES	NO
Heart Pacemaker or Defibrillator Implant	( )	( )
Aneurysm clip	( )	( )
Intravascular coils, filters and stents	( )	( )
Artificial heart valve	( )	( )
Neurostimulator Implant	( )	( )
Cochlear (inner ear) implants	( )	( )
Metallic implants or objects of any kind (including orthopedic implants)	( )	( )
Prosthetic devices	( )	( )
Artificial limb or joint	( )	( )

		YES	NO
B 2	Have you ever worked as a grinder, metal worker, machinist, welder or other occupations where you may have come in contact with small metal slivers?	( )	( )
B 3	Have you ever been injured in the head, eye or body by a metallic foreign body that was not removed? (eg. bullets, shrapnel, metallic slivers)	( )	( )
B 5	Do you have braces on your teeth or non removable dental retainers?	( )	( )
B 6	Do you have dental work held in place by magnets?	( )	( )
B 5	Do you have body piercing (non-removable metal jewellery)?	( )	( )
B 6	Is there any chance you may be pregnant?	( )	( )
	Are you breast feeding?	( )	( )
B 7	Do you have an IUD or contraceptive diaphragm?	( )	( )
B 8	Are you being treated for, or do you have a history of:		
	Claustrophobia (fear of closed spaces)	( )	( )
	Seizures	( )	( )

SECTION C

Some medical conditions can be made worse by stress. If you suffer from any of the following AND you think you may experience stress during the course of the study, please consult with your doctor before participating.

		YES	NO
C 1	Do you have:		
	Uncontrolled high blood pressure	( )	( )
	Ischemic heart disease	( )	( )
	Congestive heart disease	( )	( )
	Angina	( )	( )
	Heart palpitations	( )	( )
	Other heart disorders:	( )	( )
	Specify:______________________		
	Panic attacks	( )	( )
	Any other anxiety disorders:	( )	( )
	Specify:______________________		
	______________________		
C 2	Do you have any other illnesses?	( )	( )
	Specify:______________________		
	______________________		

SECTION D

The pigment used in some tattoos is iron based and may cause skin irritation during the MRI scan, especially if the tattoo is large and has been done recently. If you have a tattoo, please discuss with the Human Studies Co-ordinator.

		YES	NO
D 1	Do you have a tattoo?	( )	( )

All information provided on this form is accurate to the best of my knowledge.

Physician's Name: (please print) ________________________________

Physician's Address (please print) ________________________________

____

____

Physician's Signature ______________________ Date __________

Research Subject's Signature ______________________ Date __________

Appendix F

National Research Council of Canada
Consent Form

Protocol Number

February 3, 2000

CONSENT FORM

I have received a copy of and I have read the Research Study Summary. I understand the nature of the study, including the potential risks and benefits. I have had adequate time to consider the information. I have talked to Dr. Patrick Stroman and/or his colleagues. All my questions about the study have been answered. If I have any more questions, I may call Dr. Patrick Stroman at the Institute for Biodiagnostics of the National Research Council at 984-6973.

All information obtained in connection with this study and that can be identified with me will remain confidential within the limits of the law and will only be disclosed with my permission. I give permission to disclose this information to the Institute for Biodiagnostic's medical imaging specialist and the physician I have named for the purpose of follow-up.

I have named Dr. ________________ at ________________ as the physician to be contacted for follow-up purposes.

I realize that by signing this document I am not waiving any legal rights.
I hereby agree to participate in the research protocol, "**The Relationship Between Intercondylar Notch Dimensions and Anterior Cruciate Ligament (ACL) Size**" and I understand that I can end my participation at any time and for any reason.
My consent has been given freely.

____
Name of research subject (Print)

____________________________ ______________
Signature of research subject Date

____________________________ ______________________________
Name of person obtaining consent (Print) Role in study *(e.g. Investigator, MR Technologist, Study Nurse)*

____________________________ ______________
Signature of person obtaining consent Date

Subject number: ____________

Appendix G

Instructions to Subjects

Instructions to Subjects

1. Screening by a physician is a requirement to participate in this study. If any of the following are applicable to you, you may not participate in this study: you have metal objects inside your body, you have a medical condition that could be made worse by any stress associated with participation in a research protocol, including heart and circulatory conditions, seizure disorders, anxiety disorders, mental disorders, you have claustrophobia, you are or may be pregnant.

2. You must be in good health to participate in this study.

3. Your participation will involve one visit to the Health Sciences Centre MRI unit where you will have a Magnetic Resonance (MR) scan of your knee.

4. The scan itself will take approximately 90 minutes but allow a total of 2 ½ hours for the visit.

5. An appointment is needed to participate in the study. The appointment can be made through the Human Studies Coordinator at (204) 984-2433. Further information about the study can also be obtained through this number.

6. At the appointment for the scan, an investigator will go through your screening form with you to make sure there are no metal objects in your body, give you information about the study, and show you the MRI system.

7. Be sure that all your questions are answered and you agree to participate in the study before signing the informed consent form (refer to consent form attached).

8. Before you enter the magnet room, you will be asked to change into clothing which does not contain metal. You can wear your own clothing if it is metal free or a hospital gown can be provided. You can wear jeans but a jogging suit will likely be more comfortable.

9. For the scan, you will be positioned on your back and provided with earplugs to reduce the noise from the MRI scanner. The knee to be imaged will be placed inside a special MR coil shaped like a hollow cylinder with separate top and bottom halves. Your knee will initially be positioned in full extension. Padding will be placed inside the coil around your knee for comfort and to keep your knee from moving. You will then be slid, feet first into the tunnel-shaped magnet until your knee is at the centre. Your head should be near the open end of the magnet or outside depending on your height.

10. During the scan, the MR operator will be in constant communication with you through a two-way intercom.

11. After the scan is complete and you have left the magnet room, you will be asked to fill out a questionnaire. The answers will aid in investigating the frequency of any ill effects felt at the time of the scan.

12. The study is completely confidential. Only those directly involved with the research will be allowed in the area. All data will be stored with a code instead of your name.

13. MRI is completely painless, but some people have experienced minor discomfort during scans (eg. dizziness, lightheadedness, claustrophobia, or a feeling of continued motion after being moved into the magnetic field). These effects usually subside within a few minutes. Please inform us immediately of any of these effects and the study will be discontinued.

14. No long-term adverse effects of MRI have been reported. You would be contacted if any new risks are discovered. Please contact us if you experience any effects you feel may be the result of participating in this study.

15. This is a research study so you will not personally benefit from your participation. Eventually the results of the study may benefit future patients with anterior cruciate ligament (ACL) injuries.

16. You have the right to withdraw from the study at any time and for any reason without penalty. The investigators reserve the right to end you participation for any reason.

17. You will receive $25 to cover any expenses you incur to participate in this study.

18. You may request a copy of some of the images.

19. You may request a copy of the complete scientific protocol for this study. You are also entitled to know the overall scientific and technical results at the end of the project.

Appendix H

Exit Questionnaire

Exit Questionnaire

1.5 T Magnet
Research Subject Identifier:____________
Date:____________
Thank you for participating in our study. We would appreciate it if you would answer the following questions about your experience.

1) Did you experience any unusual sensations while in the magnet?
Yes ( ) No ( )
If yes, please describe (what, when, how long)

____

____

2) Please check the following:

Did you experience the following		YES	NO
a)	nervousness	( )	( )
b)	sleepiness	( )	( )
c)	dizziness	( )	( )
d)	metallic taste	( )	( )
e)	warmth	( )	( )
f)	cold	( )	( )
g)	claustrophobia	( )	( )
h)	double vision	( )	( )
i)	lightheadedness	( )	( )

Comments:____

	YES	NO
3) Would you participate in an MR study again?	( )	( )
Would you like to be contacted when you are eligible for another study?	( )	( )

4) Please tell us how we could have made your experience more comfortable

____

____

5) How did you feel about the way in which you were approached about participating in this study?

____

____

Thank you

Appendix I

MRI Protocol Sheet

PROTOCOL 2000-07 MRI of the ACL and Intercondylar Notch

Subject No: ________________ Date: ____________________
Age _____ Male ☐ Female ☐

Setup: Subject supine with right knee in the GE knee coil, entering magnet feet first
Padding placed around knee to minimize motion and for comfort
Leg and foot supported so that the knee is fully extended

Right Knee

Series 1 3-plane localizer, No Phase Wrap
FOV = 24 cm, slice = 3 mm, spacing = 0
256 x 128, 2 Nex, phase FOV = 1.0
FOV center = offset read from coil base,0,0
3 locs/plane

Series 2 Imaging Intercondylar Notch

Coronal views of the knee
Fast Spin-Echo, TR = 2400, TE = 30 and 90 msec
FOV = 14 cm, 2 averages, 256 x 154 matrix, 2 mm slices, 0.0 mm slice gap

Series 3 Repeat Series 2 with Axial views of the knee

Slice planes perpendicular to the intercondylar roof
Fast Spin-Echo, TR = 2400, TE = 30 and 90 msec
FOV = 14cm, 2 averages, 256 x 154 matrix, 2 mm slices, 0.0 mm slice gap

Series 4a Imaging of the ACL

Slices parallel to the ACL, showing its entire length as much as possible

Sagittal oblique Fast Spin-Echo, TE = 12, TR = 1300, ETL = 6
FOV = 14 cm, 256 x 256, 4 averages, slice thickness = 2 mm, contiguous slices angled off of coronal image in series 2

Series 4b Repeat Series 4a with slices angled off of axial image in series 3

Sagittal oblique Fast Spin-Echo, TE = 12, TR = 1300, ETL = 6
FOV = 14 cm, 256 x 256, 4 averages, slice thickness = 2 mm, contiguous

Series 5a Imaging of the ACL

Position slices transverse to the ACL

Axial oblique Fast Spin-Echo, TE = 28, TR = 500, 14 cm FOV, 2 mm slices, contiguous
256 x 256 interpolated to 512 x 512, 2 averages

Series 5b Repeat series 5a with slices angled off of image in series 4a

Axial oblique Fast Spin-Echo, TE = 28, TR = 500, 14 cm FOV, 2 mm slices, contiguous
256 x 256 interpolated to 512 x 512, 2 averages

Series 5c Repeat series 5a with slices angled off of images in series 4b

Axial oblique Fast Spin-Echo, TE = 28, TR = 500, 14 cm FOV, 2 mm slices, contiguous
256 x 256 interpolated to 512 x 512, 2 averages

Appendix J

Data Collection Sheet

				Subject #: S -00-07 ( )		
	Measurement 1		**Measurement 2**		**Measurement 3**	
M1 (Notch Width - Axial View)						
a) at popliteal recess						
b) at 2/3 notch height						
c) through inferior articular						
margins of femoral condyles						
M1 (Notch Width - Coronal View)						
a) at popliteal recess						
b) at 2/3 notch height						
c) through inferior articular						
margins of femoral condyles						
	axial	coronal	axial	coronal	axial	coronal
M2 (Notch Height)						
M3 (Notch Angle)						
M4 (Lateral Wall Angle)						
M5 (Greatest Medial to						
Lateral Dimension of						
Femoral Condyles)						
M6 (Femoral Condyle Width						
at popliteal recess)						
C (Notch Depth)						
ACL Length						
ACL Width						
ACL Angle of Pull						

Appendix K

Subject Demographic Data

Subject Demographics

Males	Height (cm)	Weight (kg)	Females	Height (cm)	Weight (kg)
S4	185.42	88.64	**S1**	172.72	77.27
S8	180.34	100.00	**S2**	185.42	90.91
S9	165.10	65.91	**S3**	152.40	45.45
S10	172.72	56.82	**S5**	170.18	79.55
S15	180.34	59.09	**S6**	170.18	68.18
S17	170.18	56.82	**S7**	162.56	72.73
S20A	177.80	102.27	**S11**	170.18	54.55
S21	172.72	65.91	**S12**	170.18	77.27
S22	182.88	81.82	**S13**	162.56	68.18
S24	182.88	74.09	**S14**	167.64	59.09
S27	187.96	75.00	**S16**	171.45	84.09
S28	177.80	77.27	**S18**	165.10	59.09
S29	190.50	118.18	**S19**	157.48	54.55
S31	187.96	86.36	**S20B**	175.26	81.82
S32	182.88	93.18	**S23**	172.72	75.00
S33	180.34	61.36	**S25**	182.88	90.91
			S26	167.64	54.55
			S30	163.83	61.36

Appendix L

Raw Data for Axial View MRI Intercondylar Notch Measurements for Males

	M1-A			M1-B			M1-C			M2			M3		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
S4	24.1	24.0	24.0	18.1	18.0	18.1	24.9	24.8	24.8	26.6	26.5	26.6	48.8	48.8	48.8
S8	21.9	21.8	21.9	18.6	18.5	18.6	22.5	22.4	22.4	25.2	25.1	25.2	46.5	46.5	46.4
S9	21.9	21.8	21.8	18.6	18.7	18.6	18.9	19.0	19.0	20.4	20.3	20.4	38.2	38.3	38.2
S10	28.4	28.2	28.3	18.1	18.1	18.0	26.8	26.7	26.7	16.8	16.9	16.9	59.8	59.7	59.8
S15	23.1	23.0	23.0	20.3	20.1	20.1	22.5	22.7	22.6	20.3	20.2	20.2	55.0	55.0	55.2
S17	27.3	27.3	27.2	22.4	22.4	22.3	24.9	24.8	24.8	28.4	28.3	28.3	44.5	44.4	44.4
S20A	23.6	23.7	23.7	14.0	14.1	14.0	24.3	24.1	24.1	25.2	25.2	25.1	37.9	37.9	37.9
S21	23.0	22.9	23.0	14.8	14.8	15.0	20.5	20.5	20.4	23.2	23.0	23.1	45.5	45.4	45.4
S22	22.4	22.3	22.3	17.8	17.7	17.7	18.9	18.8	18.9	24.9	24.8	24.8	38.9	38.8	38.9
S24	20.3	20.2	20.3	15.0	15.1	15.1	15.9	15.9	15.8	24.6	24.6	24.7	35.1	35.2	35.2
S27	22.2	22.3	22.2	18.1	18.2	18.2	18.4	18.3	18.3	26.0	26.1	26.1	36.3	36.4	36.3
S28	24.6	24.5	24.5	18.1	18.2	18.0	20.0	20.1	20.0	25.7	25.7	25.6	42.1	42.2	42.3
S29	26.9	26.8	26.9	20.0	20.0	20.1	23.4	23.3	23.3	24.7	24.8	24.8	49.4	49.3	49.3
S31	26.6	26.6	26.7	19.4	19.5	19.4	25.5	25.4	25.4	28.5	28.5	28.6	46.0	45.9	46.0
S32	22.9	22.8	22.8	14.1	14.2	14.2	19.5	19.5	19.4	31.4	31.5	31.4	44.1	44.0	44.0
S33	27.6	27.6	27.5	18.3	118	18.3	27.1	27.2	27.2	26.8	26.7	26.7	52.7	52.8	52.8

M4			M5			M6			C		
1	2	3	1	2	3	1	2	3	1	2	3
29.7	29.7	29.7	82.1	82.1	82.1	76.9	76.8	76.8	35.3	35.3	35.2
24.9	24.9	24.8	87.0	87.2	87.0	81.5	81.5	81.6	33.1	33.2	33.1
22.3	22.3	22.3	76.8	76.7	76.8	70.5	70.4	70.5	32.3	32.5	32.5
36.6	36.5	36.6	79.6	79.5	79.6	75.5	75.4	75.4	29.5	29.3	29.4
30.5	30.5	30.5	87.8	87.6	87.8	78.2	78.2	78.3	29.3	29.1	29.3
13.4	13.5	13.4	76.8	76.9	76.8	73.2	73.1	73.2	36.7	36.6	36.7
20.4	20.5	20.4	83.4	83.4	83.4	79.9	79.9	79.9	32.9	33.0	32.9
24.8	24.7	24.7	76.3	76.3	76.3	70.5	70.5	70.5	29.0	28.9	29.0
23.3	23.4	23.3	79.7	79.7	79.6	72.5	72.4	72.4	33.7	33.7	33.6
17.3	17.2	17.2	76.1	76.1	76.1	69.2	69.1	69.2	32.8	32.7	32.7
18.9	18.9	19.0	78.0	78.1	78.0	72.0	72.0	72.0	34.8	34.7	34.7
24.9	24.9	25.0	79.6	79.6	79.6	76.6	76.6	76.7	34.8	34.7	34.8
29.4	29.5	29.4	86.6	86.6	86.6	77.2	77.2	77.2	31.3	31.4	31.3
26.7	26.7	26.6	82.7	82.6	82.7	78.6	78.5	78.5	35.9	35.8	35.9
18.3	18.4	18.3	75.9	75.8	75.8	71.5	71.6	71.5	31.7	31.6	31.6
28.4	28.4	28.3	80.7	80.7	80.7	77.4	77.4	77.4	32.3	32.4	32.4

Axial View MRI Intercondylar Notch Measurements for Males

Appendix M

Raw Data for Coronal View MRI Intercondylar Notch Measurements for Males

	M1-A			M1-B			M1-C			M2			M3		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
S4	23.5	23.4	23.5	18.1	18.2	18.1	20.8	20.7	20.7	24.1	24.0	24.1	45.9	45.9	45.9
S8	23.1	23.2	23.0	16.4	16.5	16.5	28.1	28.0	28.0	25.5	25.5	25.3	40.3	40.4	40.3
S9	17.5	17.8	17.7	16.7	16.8	16.7	14.4	14.5	14.6	16.1	16.0	16.1	37.5	37.4	37.4
S10	20.2	20.2	20.2	14.8	14.7	14.8	20.6	20.6	20.5	13.2	13.3	13.2	68.4	68.4	68.3
S15	21.9	21.9	21.7	15.0	15.1	15.0	21.2	21.2	21.0	24.2	24.2	24.2	48.1	48.0	48.1
S17	24.3	24.4	24.4	19.1	19.2	19.1	21.6	21.7	21.6	20.9	20.9	20.8	47.9	47.8	47.9
S20A	20.0	20.1	20.0	15.3	15.2	15.3	17.8	17.8	17.9	24.4	24.4	24.3	39.2	39.2	39.1
S21	19.1	19.1	19.0	18.9	18.8	18.9	17.3	17.2	17.3	24.6	24.5	24.6	38.7	38.7	38.7
S22	20.2	20.1	20.1	16.4	16.3	16.3	16.5	16.5	16.6	20.5	20.5	20.4	36.3	36.4	36.3
S24	19.2	19.1	19.1	17.5	17.5	17.5	14.7	14.7	14.7	22.7	22.6	22.7	35.4	35.5	35.3
S27	23.0	22.9	23.0	14.8	14.7	14.7	17.6	17.5	17.6	23.3	23.4	23.4	39.4	39.4	39.3
S28	22.1	22.2	22.2	14.8	14.7	14.8	18.8	18.9	18.8	20.0	19.9	20.1	49.4	49.5	49.4
S29	24.7	24.8	24.7	19.4	19.5	19.5	21.3	21.3	21.3	26.9	27.0	26.9	40.1	40.1	40.2
S31	24.3	24.3	24.2	15.6	15.7	15.7	20.0	20.0	20.0	22.7	22.7	22.6	46.9	47.0	47.0
S32	20.2	20.2	20.2	13.4	13.5	13.4	16.8	16.7	16.7	20.2	20.1	20.1	44.5	44.6	44.6
S33	25.0	25.1	25.0	16.8	16.9	16.8	21.8	21.8	21.9	26.8	26.7	26.8	56.4	56.4	56.5

M4			M5			M6			C		
1	2	3	1	2	3	1	2	3	1	2	3
25.8	25.7	25.7	85.1	85.1	85.1	77.2	77.1	77.1	33.4	33.3	33.3
17.8	17.7	17.7	89.6	89.5	89.5	80.6	80.7	80.6	32.8	32.5	32.5
20.3	20.4	20.3	78.5	78.5	78.5	70.8	70.9	70.8	24.6	24.5	24.5
33.0	32.9	33.0	82.0	82.0	82.0	74.1	74.1	74	22.4	22.4	22.5
19.5	19.5	19.5	84.3	84.2	84.2	78.8	78.8	78.8	32.3	32.4	32.3
26.2	26.2	26.2	83.7	83.7	83.6	73.0	73.0	73.0	24.3	24.4	24.4
20.1	20.1	20.1	87.0	86.9	86.9	78.3	78.3	78.3	33.4	33.5	33.5
21.5	21.5	21.5	77.7	77.7	77.6	68.9	68.9	68.8	30.9	30.8	30.9
28.0	28.0	27.9	83.7	83.6	83.6	71.1	71.1	71.1	29.3	29.4	29.3
23.2	23.1	23.2	79.9	79.9	79.8	70.0	70.1	70.0	29.6	29.7	29.6
21.1	21.0	21.0	80.7	80.6	80.7	71.7	71.6	71.7	30.9	30.9	31.0
25.1	25.2	25.2	81.5	81.4	81.4	74.1	74.0	74.1	29.3	29.4	29.3
25.0	25.1	25.0	87.4	87.3	87.4	77.7	77.7	77.8	34.8	34.7	34.7
26.3	26.4	26.4	85.6	85.6	85.6	79.0	79.0	79.0	32.5	32.6	32.6
21.7	21.7	21.6	78.5	78.5	78.5	70.3	70.3	70.4	29.3	29.4	29.3
35.5	35.6	35.4	84.6	84.5	84.6	76.6	76.5	76.5	27.4	27.5	27.4

Coronal View MRI Intercondylar Notch Measurements for Males

Appendix N

Raw Data for Axial View MRI Intercondylar Notch Measurements for Females

	M1-A			M1-B			M1-C			M2			M3		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
S1	21.6	21.6	21.5	16.1	16.2	16.1	20.2	20.1	20.1	22.4	22.3	22.4	47.0	47.1	47.0
S2	16.3	16.3	16.4	15.3	15.3	15.4	14.3	14.4	14.4	22.5	22.5	22.6	34.1	34.1	34.2
S3	21.3	21.2	21.3	15.9	15.8	15.8	19.4	19.5	19.5	21.9	21.9	21.8	47.0	47.1	47.0
S5	17.8	17.7	17.7	15.3	15.2	15.3	18.6	18.7	18.6	21.1	21.2	21.1	42.4	42.4	42.4
S6	18.9	19.0	18.9	13.7	13.6	13.7	16.4	16.3	16.3	24.1	24.0	24.0	39.4	39.4	39.5
S7	20.6	20.7	20.6	17.8	17.7	17.9	21.7	21.8	21.7	23.9	23.9	24.0	49.4	49.4	49.4
S11	21.1	21.1	21.0	15.4	15.5	15.5	19.0	18.9	18.9	22.8	22.9	22.8	44.3	44.2	44.2
S12	22.7	22.7	22.8	19.7	19.7	19.7	19.2	19.4	19.3	23.3	23.4	23.3	44.5	44.6	44.5
S13	18.9	18.9	18.9	13.9	13.8	13.8	18.9	18.9	18.8	21.1	21.1	21.0	47.0	47.1	47.0
S14	19.5	19.4	19.4	14.7	14.7	14.8	17.6	17.8	17.8	21.3	21.2	21.2	34.6	34.7	34.7
S16	23.0	23.1	23.0	16.4	16.4	16.5	18.8	18.7	18.8	23.2	23.2	23.3	46.3	46.3	46.2
S18	19.4	19.6	19.5	13.4	13.5	13.4	17.8	17.7	17.6	20.8	20.8	20.9	43.9	43.8	43.8
S19	19.4	19.5	19.5	14.7	14.5	14.5	22.0	22.0	22.1	21.9	21.9	21.8	51.8	51.7	51.7
S20B	19.8	19.9	19.7	16.2	16.3	16.3	15.5	15.4	15.5	25.3	25.4	25.3	39.8	39.7	39.7
S23	19.0	18.9	19.0	16.5	16.5	16.4	13.4	13.4	13.4	23.6	23.4	23.5	29.2	29.2	29.2
S25	22.4	22.3	22.4	15.4	15.5	15.5	25.5	25.4	25.4	24.9	24.9	25.0	51.6	51.6	51.6
S26	21.1	21.0	21.2	13.4	13.3	13.4	20.0	20.1	20.1	23.5	23.4	23.5	42.9	42.8	42.8
S30	18.1	18.2	18.2	11.8	11.7	11.8	17.8	17.9	17.9	22.7	22.7	22.6	42.8	42.7	42.7

M4			M5			M6			C		
1	2	3	1	2	3	1	2	3	1	2	3
27.4	27.4	27.4	72.2	72.2	72.2	67.8	67.9	67.8	27.9	28.0	27.9
15.4	15.4	15.4	74.7	74.7	74.7	69.4	69.4	69.4	34.7	34.7	34.8
24.7	24.6	24.7	71.4	71.4	71.4	66.7	66.7	66.7	28.7	28.8	28.7
28.4	28.4	28.3	68.7	68.7	68.7	65.4	65.4	65.4	29.8	29.9	29.7
19.4	19.4	19.4	63.4	63.4	63.4	58.8	58.8	58.8	31.7	31.8	31.7
20.7	20.7	20.8	69.7	69.7	69.7	65.1	65.1	65.1	29.3	29.2	29.4
22.3	22.2	22.3	69.7	69.7	69.8	66.7	66.6	66.7	29.6	29.8	29.7
28.2	28.2	28.3	72.2	72.2	72.1	67.3	67.3	67.3	29.8	29.9	29.8
27.9	27.9	27.9	68.9	68.8	68.9	64.5	64.5	64.5	29.3	29.0	29.1
17.6	17.6	17.6	72.5	72.4	72.4	62.6	62.5	62.6	27.9	27.9	27.8
25.3	25.3	25.2	68.9	69	68.9	64.1	64.1	64.1	30.2	30.1	30.2
22.0	22.0	22.1	68.4	68.3	68.3	65.9	65.9	66.0	27.9	27.9	27.8
27.2	27.2	27.3	66.4	66.4	66.4	63.7	63.7	63.7	28.7	28.7	28.8
21.7	21.6	21.6	71.5	71.5	71.5	67.9	67.9	68.0	34.3	34.3	34.2
25.4	25.5	25.4	68.9	68.9	68.7	64.5	64.5	64.4	31.3	31.4	31.4
29.2	29.1	29.2	76.5	76.5	76.5	71.5	71.5	71.6	32.5	32.4	32.6
24.8	24.7	24.9	73.3	73.2	73.4	68.6	68.6	68.5	32.5	32.6	32.6
27.4	27.5	27.4	70.9	70.9	70.9	67.6	67.7	67.7	30.1	30.0	30.1

Axial View MRI Intercondylar Notch Measurements for Females

Appendix O

Raw Data for Coronal View MRI Intercondylar Notch Measurements for Females

	M1-A			M1-B			M1-C			M2			M3		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
S1	18.6	18.6	18.7	14.8	14.7	14.6	15.0	14.9	15.1	20.0	20.1	20.1	46.8	46.9	46.9
S2	16.6	16.6	16.7	12.8	12.9	12.7	12.5	12.4	12.6	22.9	23.0	22.9	25.7	25.6	25.8
S3	18.6	18.5	18.5	14.2	14.2	14.3	15.3	15.2	15.2	19.7	19.7	19.7	41.3	41.2	41.3
S5	17.2	17.1	17.1	13.9	13.8	13.8	15.4	15.3	15.4	19.1	19.0	19.0	43.4	43.3	43.3
S6	16.4	16.3	16.3	12.6	12.5	12.5	15.3	15.4	15.3	17.0	17.1	17.0	44.5	44.4	44.4
S7	21.1	21.2	21.1	18.1	18.1	18	18.9	18.8	18.9	22.2	22.3	22.3	37.3	37.3	37.2
S11	17.1	17.3	17.2	14.9	14.9	14.9	18.5	18.6	18.6	15.8	15.9	15.8	54.0	54.0	54.0
S12	18.4	18.5	18.4	13.0	13.1	13.1	17.1	17.1	17.0	17.4	17.5	17.4	49.7	49.7	49.7
S13	15.0	15.0	15.1	10.9	10.8	10.8	16.2	16.4	16.4	15.0	15.1	15.1	55.7	55.6	55.6
S14	17.5	17.5	17.5	14.5	14.5	14.4	15.3	15.2	15.3	24.0	24.1	24.0	40.3	40.2	40.1
S16	22.3	22.3	22.3	12.7	12.8	12.8	20.5	20.5	20.5	18.4	18.4	18.5	61.5	61.4	61.4
S18	15.9	15.8	15.9	13.4	13.5	13.5	12.3	12.2	12.2	20.8	20.7	20.7	31.5	31.6	31.5
S19	17.2	17.2	17.2	13.4	13.5	13.4	18.3	18.3	18.4	19.2	19.2	19.3	48.0	48.0	47.9
S20B	18.9	19.0	18.9	14.2	14.2	14.2	13.5	13.4	13.5	22.5	22.6	22.6	53.3	53.2	53.2
S23	18.4	18.5	18.4	15.4	15.6	15.5	14.6	14.7	14.6	22.2	22.1	22.2	36.4	36.2	36.3
S25	19.4	19.3	19.3	15.3	15.5	15.4	19.1	19.0	19.1	22.2	22.2	22.3	44.2	44.2	44.1
S26	18.9	18.8	18.9	16.2	16.3	16.2	17.0	17.0	17.1	21.9	22.0	21.9	42.3	42.4	42.2
S30	17.0	16.9	17.0	14.3	14.4	14.3	15.7	15.7	15.6	23.0	22.9	23.0	37.0	37.1	37.0

M4			M5			M6			C		
1	2	3	1	2	3	1	2	3	1	2	3
27.6	27.5	27.5	73.3	73.2	73.4	66.5	66.5	66.5	27.3	27.2	27.3
17.0	17.0	17.0	79.7	79.7	79.7	71.9	71.9	71.9	32.9	33.0	32.9
21.8	21.9	21.8	73.6	73.6	73.6	66.7	66.7	66.7	28.2	28.3	28.4
26.1	26.1	26.2	71.4	71.4	71.4	65.1	65.0	65.1	26.2	26.1	26.1
26.2	26.2	26.1	66.5	66.6	66.6	58.8	58.8	58.8	25.7	25.8	25.8
22.1	22.2	22.2	73.3	73.3	73.4	67.0	67.0	67.1	30.7	30.6	30.8
35.1	35.2	35.1	72.2	72.2	72.2	65.4	65.3	65.4	23.2	23.2	23.2
33.8	33.8	33.9	77.1	77.1	77.0	68.6	68.6	68.6	25.5	25.7	25.5
28.4	28.4	28.4	72.2	72.3	72.2	64.3	64.2	64.3	23.0	23.0	23.1
34.0	34.0	34.0	68.6	68.7	68.7	62.8	62.7	62.8	30.9	30.7	30.9
44.7	44.7	44.8	71.2	71.3	71.2	64.7	64.7	64.7	27.9	27.9	27.8
17.8	17.7	17.8	71.1	71.2	71.2	64.3	64.4	64.4	26.8	26.9	26.9
27.8	27.9	27.8	71.1	71.1	71.1	63.7	63.7	63.7	26.6	26.7	26.6
23.6	23.5	23.5	78.7	78.8	78.8	67.4	67.3	67.3	30.4	30.4	30.5
24.4	24.4	24.4	73.4	73.3	73.4	66.8	66.7	66.7	27.4	27.4	27.4
23.9	24.0	23.9	79.1	79.1	79.0	70.3	70.4	70.3	32.2	32.3	32.3
24.8	24.9	24.9	77.2	77.3	77.3	67.4	67.5	67.5	31.2	31.1	31.1
21.1	21.2	21.2	75.0	75.1	75.0	68.2	68.2	68.2	30.1	30.0	30.1

Coronal View MRI Intercondylar Notch Measurements for Females

Appendix P

Raw Anterior Cruciate Ligament (ACL) Data for Males

	ACL Length			ACL Width			ACL Angle of Pull		
	1	2	3	1	2	3	1	2	3
S04	36.0	36.0	36.2	4.9	4.9	4.9	29.2	29.5	29.2
S08	42.4	42.2	42.3	5.6	5.5	5.6	19.3	19.5	19.5
S09	38.2	38.4	38.2	3.3	3.4	3.4	17.4	17.5	17.5
S10	36.4	36.6	36.4	4.3	4.4	4.4	37.0	36.0	37.0
S15	41.9	41.8	42.0	5.5	5.6	5.6	30.8	30.7	30.8
S17	41.4	41.3	41.4	3.3	3.3	3.4	25.7	25.8	25.9
S20A	42.4	42.2	42.1	5.2	5.3	5.2	12.6	12.8	12.6
S21	38.8	39.0	38.9	5.7	5.7	5.6	30.0	29.9	29.9
S22	40.4	40.6	40.5	5.2	5.2	5.2	25.5	25.7	25.6
S24	40.1	40.0	40.2	3.8	4.1	4	21.5	21.6	21.7
S27	39.6	39.9	39.9	5.3	5.4	5.3	25.0	25.0	25.1
S28	38.6	38.5	38.6	4.4	4.4	4.3	25.1	24.9	25.0
S29	43.3	43.4	43.3	5.7	5.7	5.7	24.5	24.5	24.5
S31	41.8	41.8	41.8	4.4	4.4	4.4	31.1	31.4	31.2
S32	38.9	38.8	38.9	4.4	4.2	4.3	24.0	23.8	23.8
S33	36.2	36.2	36.4	4.3	4.4	4.6	31.6	30.5	31.2

Raw Anterior Cruciate Ligament (ACL) Data for Males

Appendix Q

Raw Anterior Cruciate Ligament (ACL) Data for Females

	ACL Length			ACL Width			ACL Angle of Pull		
	1	2	3	1	2	3	1	2	3
S1	32.1	32.2	32.3	4.1	4.2	4.1	26.1	26.1	26.2
S2	35.0	35.2	35.1	5.3	5.4	5.3	27.0	27.2	27.1
S3	31.9	31.8	31.8	4.1	4.1	4.1	30.0	29.5	29.9
S5	32.5	32.7	32.6	5.5	5.7	5.5	20.2	20.2	20.4
S6	31.4	31.8	31.4	4.1	4.1	4.2	24.1	24.1	24.2
S7	41.9	42.0	42.1	6.0	5.9	6.0	24.8	24.9	24.8
S11	35.8	35.7	35.7	4.9	4.9	5.0	21.7	21.6	21.6
S12	37.6	37.8	37.8	5.7	5.6	5.8	24.6	24.8	24.8
S13	35.1	35.0	35.1	4.9	5.0	5.0	21.5	21.6	21.6
S14	36.0	36.1	36.2	4.1	4.3	4.3	22.6	22.6	22.6
S16	32.5	32.6	32.6	5.3	5.2	5.2	48.4	48.3	48.4
S18	34.1	34.3	34.2	4.1	4.2	4.2	20.6	20.7	20.8
S19	32.5	32.3	32.3	5.5	5.5	5.5	29.9	29.7	29.9
S20B	34.6	34.6	34.7	4.5	4.3	4.5	25.9	26.2	25.9
S23	30.9	31.0	31.1	4.6	4.4	4.5	31.9	32.2	32.0
S25	37.9	37.7	37.7	4.4	4.7	4.7	28.4	28.2	28.2
S26	34.4	34.2	34.4	3.3	3.0	3.1	28.7	28.4	28.6
S30	34.8	34.6	34.5	3.8	3.9	3.9	29.9	30.0	30.1

Raw Anterior Cruciate Ligament (ACL) Data for Females

Appendix R

ANOVA Tables for Axial Stepwise Multiple Linear Regression

ANOVA Tables for Axial Stepwise Multiple Linear Regression

Model		Sum of Squares	df	Mean Square	F	P value
5	Regression	243.249	5	48.650	32.039	0.001
	Residual	42.517	28	1.518		
	Total	285.767	33			
2	Regression	98.806	2	49.403	16.716	0.001
	Residual	91.619	31	2.955		
	Total	190.425	33			
3	Regression	346.001	3	115.334	62.035	0.001
	Residual	55.775	30	1.859		
	Total	401.776	33			
2	Regression	100.154	2	50.077	11.706	0.001
	Residual	132.619	31	4.278		
	Total	232.773	33			
3	Regression	965.341	3	321.780	41.496	0.001
	Residual	232.634	30	7.754		
	Total	1197.975	33			
2	Regression	314.151	2	157.075	9.440	0.001
	Residual	515.836	31	16.640		
	Total	829.987	33			
4	Regression	1187.262	4	296.816	227.791	0.001
	Residual	37.787	29	1.303		
	Total	1225.050	33			
2	Regression	1005.035	2	502.518	333.102	0.001
	Residual	46.767	31	1.509		
	Total	1051.802	33			
2	Regression	106.317	2	53.158	11.842	0.001
	Residual	139.157	31	4.489		
	Total	245.474	33			
3	Regression	332.139	3	110.713	29.752	0.001
	Residual	111.637	30	3.721		
	Total	443.776	33			
1	Regression	3.297	1	3.297	6.870	0.013
	Residual	15.356	32	0.480		
	Total	18.653	33			
3	Regression	443.857	3	147.952	5.528	0.004
	Residual	802.948	30	26.765		
	Total	1246.805	33			

Appendix S

ANOVA Tables for Coronal Stepwise Multiple Linear Regression

ANOVA Tables for Coronal Stepwise Multiple Linear Regression

Model		Sum of Squares	df	Mean Square	F	P value
7	Regression	210.858	5	42.172	27.710	0.001
	Residual	42.613	28	1.522		
	Total	253.471	33			
2	Regression	75.635	2	37.817	19.384	0.001
	Residual	60.478	31	1.951		
	Total	136.113	33			
2	Regression	215.067	2	107.534	26.132	0.001
	Residual	127.566	31	4.115		
	Total	342.634	33			
2	Regression	256.703	2	128.352	46.890	0.001
	Residual	84.856	31	2.737		
	Total	341.559	33			
1	Regression	1736.703	1	1736.703	57.958	0.001
	Residual	958.882	32	29.965		
	Total	2695.585	33			
2	Regression	819.868	2	409.934	37.678	0.001
	Residual	337.282	31	10.880		
	Total	1157.150	33			
2	Regression	1091.896	2	545.948	283.724	0.001
	Residual	59.651	31	1.924		
	Total	1151.546	33			
1	Regression	897.341	1	897.341	491.077	0.001
	Residual	58.473	32	1.827		
	Total	955.814	33			
2	Regression	267.702	2	133.851	53.743	0.001
	Residual	77.208	31	2.491		
	Total	344.911	33			
3	Regression	337.111	3	112.370	31.604	0.001
	Residual	106.666	30	3.556		
	Total	443.776	33			
1	Regression	3.297	1	3.297	6.870	0.013
	Residual	15.356	32	0.480		
	Total	18.653	33			
1	Regression	454.165	1	454.165	18.335	0.001
	Residual	792.640	32	24.770		
	Total	1246.805	33			