Injury and repair of the anterior cruciate ligament

Catherine Chenot
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by

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The anterior cruciate ligament (ACL), a primary supporting ligament of the knee, has become the focus of considerable medical research. Tremendous stress is exerted on this ligament every day, particularly for the athlete. Partial and complete tears prevent athletes from competing for several months at a time, often resulting in the individual's loss of pay as well as the team's loss of a player. Naturally, a short, effective recovery is what most physicians are trying to perfect.

In addition to being involved in sports personally, several of my friends have experienced a knee injury of some sort. Being concerned with the complications, I dove into the subject matter, only to find a vast amount of research. The ACL, perhaps the most common site of injury in athletes, became the focus for this thesis.

I present my research to the general public, and especially to those who face rehabilitation or surgery. It is this population that I am educating on our current knowledge and techniques.

The fine arts and the medical fields are not usually associated together, however without illustrations, the
teaching of medicine would be a difficult task. Not only do students refer to diagrams constantly, but surgeons study new techniques through illustration and even the layman can be educated on complex medical disorders and corrections through illustration. Of my own particular interest is the patient who experiences complications and wishes to learn more about them, whether it be the process of damage or the repair involved. It is crucial that the patient realize the benefits and consequences of each procedure available, particularly in cases such as ACL tears, in which the patient has a choice of various corrections, namely nonoperative or operative. He should be educated on his own corrective options as well as his anticipated recovery, depending on which procedure is chosen. In addition, it is likely that operations will be more successful when the patient realizes the ramification of the injury, repair, and recovery, as he will be ultimately responsible for the rehabilitation and can alter the effectiveness of the surgeon's performance.

Naturally, with centuries of research and practice, there are numerous nonoperative and operative procedures. Through my research, however, I chose to highlight the most current and popular of those procedures. It should be noted that there are many additional techniques not mentioned that differ in measurement, site of incision, graft selection, and recovery program. For the physician who chooses to use an article such as this to instruct his patients, I would advise him to include any additional appropriate practices.
My research does contain several studies of ACL tears and resulting figures which often exhibit data that appear broad, perhaps unsubstantial. With so much research being conducted at this time, and so many surgeons carrying it out, results are bound to vary. The data I report in this paper is representative of an amalgamation of reports. Obviously, with such a wide range of results worldwide, ACL repairs have not been comprehensively regulated and there certainly is room for improvement in our current techniques.

I feel that with a more widespread education in this topic, as well as other medical complications, more research and practice will be sparked. As the general public becomes more knowledgeable, they will cooperate as well by reporting injuries and choosing the most applicable repairs. Our best defense against disease and injury today is the education of the public from the start.

The research and illustrations that I have prepared in the last few months have been a great educational factor during my schooling at RIT. Not only did the information pertain to my interests, but it reinforced my desire to become a medical illustrator. It is true that I enjoyed the researching of techniques, but of special interest to me was the execution of the illustrations.
The knee has been considered the "pedestal" of body motion by one author.¹ True, these joints support our entire weight, providing a stable base for the rest of our body. Yet the knee still allows sudden movement changes in rotations as well as acceleration and deceleration. It is no wonder, then, that if there is any deficient part, difficulties and even damage can force a person off their feet for days or weeks at a time. In fact, knee injuries are one of the most common injuries occurring in sports.

In addition to injuries, age can have a great impact on the stability of the knee. Articular cartilage in the knee gradually wears away, leading to pain, disability and eventual malfunctioning.

Congenital or developmental abnormalities may also increase wear of the knee², especially if there are malalignments of the structures. Interferences with regular movement or excessive excursion from the original positioning will prematurely wear the knee to the point where the patient may have difficulty with the simple task of walking.

Knee injuries have been recognized and studied for a surprising number of years. As early as 1558 a doctor named
Pare performed what was believed to be the first surgical knee correction.\textsuperscript{3} Reportedly, Pare removed a "loose body", some torn material, from a knee joint. For centuries afterwards, however, surgery was not a popular treatment, as there were high incidences of postoperative infections. In addition, anesthesia had yet to be discovered. Not until the nineteenth century were knee surgeries extensively practiced, especially with the growing use of antiseptic, greatly decreasing the occurrences of infections. A Dr. Annandale first introduced antiseptic precautions in knee joint surgeries and utilized them frequently in the removal of "loose cartilages" and other knee procedures.\textsuperscript{4}

The synovectomy, removal of the synovial membrane, was first introduced to Europe by Volkman as a surgical treatment for tuberculosis of the knee joint.\textsuperscript{5} The method proved to be even more worthy, however, when in 1900, Goldthwait, an American doctor, adapted the technique for nontubercular chronic arthritis.

Arthroplasty, repair of a joint surgically, was improved by Smith-Peterson and several other surgeons\textsuperscript{6} as early as 1925, while they utilized glass, viscaloid, and Vitallium. Total joint replacements made their debut in 1940.\textsuperscript{7} Vitallium plates were found to be an ideal resource as they would easily mold to the shape of the knee condyles.

Obviously, knee problems were of growing interest to the early surgeons, and research became more specialized for
specific problems. For example, following close behind these exciting new findings, ACL repair techniques were becoming valuable treatments for an all-too-common injury. Dr. Robson in 1842 and Dr. Battle in 1848 were already performing minor surgeries on the ACL. A Dr. Stark introduced a more conservative method of treatment in 1850. His injured patient was immobilized in a cast for several weeks while the torn ACL repaired itself.

Doctors Hogarth and Pringle reported in 1906 reattaching the ACL to the anterior tibial spine following a tear of the ligament. Anesthesia was used to accommodate Dr. Goetjes' detailed surgical repairs of the ACL in 1913. Before this time extensive surgeries had been rare as they often demanded more time than available under pre-existing sleep methods.

ACL reconstruction was introduced in 1917 by Dr. Hey Groves in England. He used an iliotibial tract section, inserted through drill holes through the femur and tibia, to take the place of the original ACL. In 1936, Dr. Campbell modified this procedure using the patellar tendon as a graft. In 1938 Ivan Palmer authored a text titled On the Injuries to the Ligaments of the Knee Joint which described the anatomy and gradual evolution of knee surgeries up until that time. The edition was, and still is, considered an important source of ground ideas for the philosophies and operative techniques of the knee ligaments.
More contemporary techniques were being developed throughout the mid-twentieth century. In the 1960's, a procedure existed which Feagin and Curl were still utilizing in recent years.\textsuperscript{15} Reportedly, they used "a chromic or mersilene figure eight suture in the ACL and passed this through one or two parallel drill holes in the lateral femoral condyle". Follow up studies shortly after surgery produced adequate results, however, in time most of these patients experienced knee failure once again. The technique has, of course, been outdated by this time with the introduction of new surgical techniques, including notchplasty, the widening of the bone notches, and improved rehabilitating programs which have helped make ACL injuries less of a trauma.

In 1982, Marshall and coworkers\textsuperscript{16} were producing good to excellent results on ACL repairs. 70 patients, all involved in sports, were studied. 61 of these patients received multiple loop sutures of different depths to both ACL stumps. The other 9 patients' knees were augmented with primary fascia. Follow-ups ranging from 12-90 months revealed no giving way, and none required additional meniscal repair.

In 1987 and 1988 Higgins and Steadman\textsuperscript{17} were performing very successful ACL repairs with some substantial procedural changes compared to those used previously. First, notchplasty had been adopted. Second, a multiple suture technique was performed which also involved suturing the
ligament graft to bone. Third, the technique only was to be applied to patients with proximal tears (tears at or below the ligament's midline). Fourth, advances in rehabilitation, particularly immediately after surgery, were applied, including immobilization. The last change involved extra-articular procedures which were designed to reinforce the repaired ligament.

Steadman\textsuperscript{18} recognized four types of ACL tears, with the distinctions depending on the location of the tear. Proximal tears, that is, proximal to the midline of the ligament, constitute approximately half of the ACL injuries sustained. The rest of ACL tears are either middle, combined (more than one tear), or distal tears. Of the four types, only the proximal tears would be considered by this author for primary repair. He had not been as successful with the other three in the past. Primary repair constitutes simply a reattaching of the ligament's stumps, and may or may not include extra-articular augmentation. It is not the standard procedure used for proximal tears, however it is often used as an alternative to intra-articular reconstructions.

Steadman's prescribed primary repair technique involves complete diagnosis of the injured knee arthroscopically and applicable meniscal repairs performed prior to ACL repair.\textsuperscript{19} Notchplasty between the condyles is performed to allow for better visualization of the work site. The outer layers of bone at the femoral origin of the ACL are carved away to the
depth of blood supply (preparing a "bleeding bone bed") and then a drill hole is made from this site out through the lateral femoral condyle. Double loop sutures are made along the length of the distal stump, in effect gathering the stump together and causing its end to situate against the bleeding bone bed. Half of the suture ends are pulled up through the drill hole while the others are guided behind and up over the lateral condyle, then tied individually on the side of the femur, allowing different tensions at different depths of suture, providing greater support, particularly if one or two sutures do fail.

A lateral capsular ligament reconstruction, an extra-articular procedure, is often used to provide extra support in limiting the forward translation of the tibia.\textsuperscript{20} Steadman found that this procedure not only improved the recovery times but also improved functional results in follow-up examinations. The procedure begins with a 1.5 cm by 10 cm strip of the iliotibial tract, including the characteristically stronger posterior portion of this tendon, which is separated and then split into two bands that will perform like the anterior and posterior portions of the ACL. A bone screw is inserted at the posterolateral edge of the femoral condyle. Sutures are used simply to reinforce both portions of the separated band, and then the anterior portion is cut proximally and wound tightly around the screw. The screw is driven firmly into the bone, while grounding the posterior portion against the femur. Finally this latter
portion is also cut free from its proximal end. This bolted tendon manages to support much of the stress on the knee by preventing forward translation, once again, of the the tibia. The knee should be flexed and extended to check for range of motion, and, in addition, negative Lachman and anterior drawer tests (to be discussed later) should be confirmed.
ACL injuries are certainly not a rarity, especially in the world of sports. 250,000 patients a year suffer an ACL tear\textsuperscript{21}, nine times the number that suffer from posterior cruciate ligament (PCL) injuries. While football, basketball, and hockey rank high in injuries, skiing, a sport that sends more than its share of athletes off the slopes due to ACL complications, shows an increasing number of injuries, especially in the last twenty years.\textsuperscript{22} These results can be attributed to higher boots that mainly emphasize posterior support, terrain changes, and more skiers on the slopes. Whatever the cause, this very small yet very important ligament will require special attention when something gets torn or twisted the wrong way.

When visiting a doctor, one of the first symptoms a patient with an ACL injury will mention is the pain in the knee joint. Not only will he notice it during strenuous activity, but the pain may also afflict him in his daily living. With even the lightest weight load or twist of the leg, the ACL is called upon for support, and if it is injured, it will continue to remind the patient.
With an ACL tear and associated complications the knee will have a tendency for 'giving way' in which it will buckle under the weight of the person. Usually the patient will be unsure of his knee strength, as if it can no longer support him. 'giving way' occurs in 17-65% of the cases.\(^{23}\) Additionally, mild swelling will occur, most noticeably after periods of activity in which the ACL has been needed.

The instability of the knee increases with time as the injury to the ACL progresses. In addition, the progression of deterioration is observed of secondary stabilizing structures, particularly in the menisci.\(^ {24}\) The two menisci of each knee play an important role for weight distribution and stability by strategically decreasing the stress on any one specific area. With a damaged ACL, however, additional stress is placed on these valuable menisci and wear and eventual tear speeds up. As the menisci are torn, the 'giving way' symptom occurs more often too.

It is often helpful for the physician to understand the positioning of the leg and action involved at the time of the accident. Realizing how the leg was abnormally twisted or contorted may contribute to his choice of diagnostic approach and repair procedure as very possibly he can predict the severity of the injury and damage caused to surrounding structures.\(^ {25}\) The most common mode of injury is direct contact while the knee has been rotated externally with the
valgus stress applied. In this case, another structure, the medial collateral ligament, will usually be injured as well.

The second most common injury occurs while the knee is in hyperextension. A severe blow will tear the ACL and menisci, and, in severe cases, also disrupt the PCL.

A flexed knee with a severe blow applied becomes the third most common injury. In this case the tibia will become displaced upon the femur, resulting in damage to the ACL and sometimes the PCL.

Finally, a varus load applied to a flexed knee is the fourth cause of ACL injury. Often the iliotibial tract and other lateral structures will also be disrupted.
The knee is a complex structure of bones, muscles, and ligaments which allow for a variety of motions including flexion and extension as well as some limited rotation. Nonetheless, considering the tremendous amounts of stress placed on our knees, with all the standing, walking, and driving that we do in a day, the knees hold up surprisingly well. For most people, complaints of knee pain, swelling, and 'giving way' are rare, but unfortunately some people do experience these symptoms with the onset and progression of instability of ligaments, osseous structures, menisci, and muscles.²⁶

The leg muscles are responsible for a good deal of the stability of the leg. When they are fatigued, however, they provide less support than they need to, therefore the ligaments assume more responsibility. Especially with greater forces, these ligaments are twisted and stretched, eventually causing wear and allowing for abnormal motions. The knee's performance often becomes limited, taking many athletes out of their games.

Of particular importance are two ligaments, the ACL and PCL, which cooperate in prevention of anterior displacement.
and posterior displacement, respectively, of the tibia on the femur. Presumably for its greater tensile strength, the PCL is damaged with considerably less frequency.\textsuperscript{27} The ACL on the other hand, is one of the most commonly injured ligaments of the body.

The ACL, a small bundle of fibers, averages 3.8 cm in length and 1.1 cm in width.\textsuperscript{28} Its crescent-shaped origin is at the "most posterior aspect of the medial surface of the lateral femoral condyle."\textsuperscript{29} It twists medially as it stretches to its distal attachment in front of the anterior tibial spine. The middle, medial, and lateral inferior genicular arteries are the vascularization for this very important ligament.

Injuries to the ACL often result from a valgus stress (lateral rotation of the tibia) occurring to a flexed, externally rotated knee.\textsuperscript{30} In most of these cases, a triad of injuries happen, involving the ACL, PCL, and medial meniscus. Also frequently involved are the collateral ligaments, knee capsule, gastrocnemius tendon, popliteal tendon, bone fractures, and damaged arteries and nerves.\textsuperscript{31} Maruyama and Jackson\textsuperscript{32} found that 81\% of injuries including the ACL also exhibit damage to the PCL, menisci, capsule, or collateral ligaments. Only 19\% of cases were isolated ACL injuries! One third of ACL lesions are partial with some fibrous bands still functioning\textsuperscript{33}, however, more often the tear will be
complete, requiring treatments which demand more time as well as more money from the patient.

At this time a couple generalized terms should be understood. Acute injuries are those that have occurred within the past three weeks, as during this time the effects of the injury have had most impact. Fortunately the ACL may still be partially intact and contribute to the repair of the knee.

Chronic cases are three weeks old or more. By this time, the patient has usually realized the limitations placed on the knee due to damage. Unfortunately, with prolonged wear on a damaged knee, degenerative changes may be evident, such as with the menisci and other ligaments.

Two terms, laxity and instability, are often used to describe an injured knee afflicted with an ACL tear. These terms are confused many times, understandably, as they are closely associated together in the case of an injured joint. Knee laxity refers to the slackness of the ligaments. With excessive laxity, the patient experiences occasional or regular displacement of the joint, leading to the 'giving way' symptom that many patients complain of. Laxity is variable from person to person, therefore the physician should take care to examine each patient as an individual, not setting any one as a standard. Both legs should be tested, in order to compare the laxity of the healthy to the injured knee.
Instability suggests insufficient joint support due to the abnormal laxity of the ligaments. It is not uncommon to see displacement of the joint in this case. It is a pathologic condition, an irregular change, in the knee's construction, and often leads to disability. Throughout the study of knee injuries these terms will appear and the comprehension of them will help the physician, student, or patient realize the complications and procedures that follow.

In an acute injury, with the onset of a dislocation, the patient will often notice swelling around the knee, even if the leg appears in proper position once again (where spontaneous reduction, or return to original position, has probably occurred). With extensive dislocation and possible vessel constrictions, precautions should be taken for ischemia for with oxygen depletion of the injured knee the patient may face serious consequences. Chances of recovery for the leg dwindle after 6 hours of ischemia, and after 8 the surgeon will often consider amputation.

In cases of chronic ligamentous instability, usually either a cruciate or meniscal injury or some muscle weakness has been the long-term cause. Most often, an unrecognized ACL rupture is to blame, and as with other causes, will lead eventually to functional instability of the entire knee. The patient will complain of 'catching and locking' where the joint hyperextends and holds in place due to loss of meniscal padding. While 60% of ACL tears accompany a meniscal injury,
the latter is often not discovered until arthroscopy is performed during examination of the knee. Menisci preservation is crucial in guarding against future wear and tear of the knee. A partial or complete meniscectomy is probable, however if the patient only experiences a peripheral rim tear, the meniscus should be reattached. In this case, however, immediate ACL stabilization is recommended. If a portion of the meniscus is removed, on the other hand, patients will most certainly experience instability of that knee in the future.

Initial examination of the patient includes the position of the leg, namely whether or not it is still dislocated. The condition of the skin may substantiate bruising or open wounds, and the extent of swelling may suggest the seriousness of the injury. Pulse is monitored on both legs, as well as temperature, to ensure that there is adequate blood flow.

A Doppler study or the more specific arteriogram should be run if vascularization is of concern to the physician. In addition, especially in the chronic condition an electromyogram or nerve conduction velocity study may be run to determine the present and future neurologic status of the leg. Radiographs are usually run on the patient to detect any fractures, or a "floating knee" in which the joint structures are not effectively held in place by their tendons and ligaments.
With suspicion of anterior cruciate laxity, the physician will run a series of clinical tests on the patient to assess the injury of the knee. Three more common procedures are discussed and illustrated, including the anterior drawer test, Lachman's test, and the pivot-shift test. Each of these tests will demonstrate a deficient ACL with or without the additional complications of rotation.
Anterior Drawer Test

The anterior drawer test is designed to confirm and assess the anterior translation of the tibia, approximated in millimeters. While the patient is supine, the knee is flexed 60°-90°. It is suggested that the examiner sit on the foot or steady it firmly. With the foot remaining in a neutral position, and an anterior force applied by the examiner, a healthy knee will extend slightly further forward at the lateral tibial plateau than at the medial tibial plateau. By comparing the injured knee to the healthy knee, displacement, measured in millimeters, can be recorded. The lower leg is rotated 15° externally with an anterior force, and anterior displacement of the medial tibial plateau is estimated. If the ACL is torn, tibial translation will be evident. Finally, the lower leg is rotated 30° internally with anterior force, while the iliotibial tract, lateral structures, and PCL tighten. If, in fact, any or several of these are damaged, there will be displacement of the lateral tibial plateau.

Translation of the knee structures is measured in millimeters and suggests to the examiner the severity of the injury. From there the examiner can prescribe more tests and even consider the extent of repair necessary.
Lachman's Test\textsuperscript{43}

Lachman's test is a simpler but less accurate procedure for identifying a deficient ACL. With the knee flexed at 20° the examiner, standing to the side of the patient, grasps the femur with one hand and pulls the tibia anteriorly with the other. An excessive anterior translation of the tibia in relation to the femur is a positive test result which is then estimated on a scale of:

\begin{align*}
0 & = \text{no displacement} \\
1+ & = \text{up to 5 mm displacement} \\
2+ & = \text{6 to 10 mm displacement} \\
3+ & = \text{11 to 15 mm displacement}
\end{align*}

The greater the displacement appears, of course the more serious the injury is. Often the examiner can even determine if a tear is partial or complete by the extent of translation he observes.
Pivot-Shift Test\textsuperscript{44}

The pivot-shift phenomenon, best known for its development by MacIntosh and Galway, begins with the patient's leg fully extended. As the lower leg is rotated internally, a valgus anterior stress is applied to the lateral tibial condyle and the knee is slowly flexed. In the case of ACL deficiency, the lateral femoral condyle will become displaced to the posterior slope of the lateral tibial condyle. When the knee is at $20^\circ$-$40^\circ$ of flexion, the knee will jerk suddenly as the tibia is reduced back into place due to pull from the iliotibial tract.
All the preceding tests are most effective in the chronic injury rather than in the acute. Because of the pain, swelling, limited motion or hamstring spasms associated with an acute disruption, the patient will tend to tense up at any movement, guarding himself against the discomfort. In addition, secondary restraints in the knee have probably stretched in a chronic case, and the leg will be more relaxed.

Naturally, the most cost-effective diagnosis of a knee injury is the physical examination and the consideration of the patient's history (whether or not he has had complications in the past). Technological tests are used as a tool for the clinician in examining and assessing the damage, however, unfortunately they are often misused as substitutes for more sensible physical examination methods. The patient should be warned that often a plain radiograph can supply the physician with ample information.

The plain radiograph is a standard and inexpensive technique that supplies a number of views of the knee from which the physician can usually decipher the extent of the injury and prescribe the most effective treatment method. X-rays are taken at four different positions usually, including the anteroposterior projection in which the patient stands and a series of images are recorded from the front. This view will demonstrate angulation of the knee in a varus or valgus direction. With the patient lying on his side and
flexing his leg 45°, the lateral projections are taken from the medial side. These images portray displacement of the patella. Lying face down and flexing his knee 45° again, the patient's intercondylar notch projection is recorded from the back of the knee. In this case femoral lesions or loose bodies can be detected. The last of the four projections requires the patient to lie supine with his leg flexed 45°. The patellofemoral joint projection, taken from the front allows the physician to determine the exact location of the patella.

Plain radiographs will supply crucial information and are usually a part of the routine examination, however if specific information is necessary, such as diagnosis of soft tissues, the following two tests are often performed after the physical examinations.

Magnetic Resonance Imaging (MRI) involves a specific magnetic force that attracts the hydrogen nuclei, causing them to all line up together. Once the radio wave is turned off, the nuclei enter a state of relaxation and a radio frequency signal is displayed. Normally MRI images designate bone, tendon, ligament, and fibrocartilage with black, muscle with gray, and fat and bone marrow with white. With the patient supine, images 5 mm thick are recorded of the injured knee to determine the extent of damage. MRI is used most often for the diagnosis of soft tissue such as the ACL.
Another test that in recent years has been almost replaced by MRI, arthrography\(^{48}\), is still used from time to time in case the MRI is not available or too costly. First the knee is aspirated, removing the synovial fluid from the site. Air is pumped into the site allowing the membranes to spread out, therefore increasing the visibility. With both varus and valgus stresses applied to the knee, six exposures are made as the patient rotates 30° before each exposure. Then, with the knee flexed at 90°, a lateral radiographs taken for specific study of the cruciate ligaments. The arthrography is particularly helpful in the assessment of damage of the menisci and cruciate ligaments.

An ACL injury left untreated will produce "stretching of secondary restraints, rotational instabilities, functional instabilities, increasing meniscal injury rates, and subsequent cartilaginous injuries and premature degeneration of the joint".\(^{49}\) However, delaying a surgery for 1-3 weeks after injury is strongly recommended in order for the effects of the accident, especially swelling and bruising, to subside.\(^{50}\) This is to ensure optimum range of motion during and after the recovery.

The physician's chosen method of treatment, whether operative or nonoperative, should depend on several factors including the age of the patient, the condition of the joint, and the activity level of the patient.\(^{51}\) Elderly patients especially do not require the intense knee strength that a
younger, more active patient does; they often undergo a nonsurgical treatment of bracing the knee, strengthening the muscles, and modifying their activities in order not to strain the joint again.

The extent of the injury, whether the tear is partial or complete, and whether or not there are associated collateral ligament, meniscal or bone injuries, should also steer the examiner to the most practical method. For example, a patient with a partial tear does have a better chance of returning to the pre-injury level, a lower risk of reinjury, a higher performance level, less pain and 'giving way', and a lower chance of necessary reconstruction than a patient with a complete tear treated nonoperatively. Not only is the ligament partially connected to begin with, but the intact portion of the ACL may only need strengthening or reinforcement, often requiring only nonoperative or augmentative procedures.

The most important factor influencing the examiner's and patient's decision of treatment should be the expected performance level of the patient upon recovery. Patients requiring great knee strength (athletes and those on their feet often) are likely candidates for augmentation or reconstruction. Surgery will usually arrest meniscal damage and, compared to the knee treated nonsurgically, it will be all around stronger, more useful, with the supplemental or substituted ACL. Follow-up studies demonstrate that high-
demand patients (strenuous laborers, athletes) have had better results with reconstructive surgeries than with nonoperative methods. They reported a higher performance level and fewer symptoms. Low-demand patients (sedentary people, low-impact athletes) displayed better results with non-operative procedures, as they regained sufficient use of the knee minus the impact of surgery.54

An animal study observing a recovery period of 2-52 weeks demonstrated the impacts of partial versus complete tears55, all left untreated. ACL's that were completely transected showed no self-rehabilitation while those that were partially transected displayed slow and sometimes incomplete rehabilitation. In the immature rabbit, the regenerated ligament reached 2/3 the strength of the contralateral knee; in the mature rabbit, it reached 3/4 the strength. These studies only reinforce the ideas of reconstruction, especially for the athlete requiring ligament strength.

The ACL does not heal by itself easily, and for several reasons at least an augmentation is preferred, even for a minor tear. Several benefits exist including first the transplanted tissue which becomes a framework, providing alignment for the original tear as it heals. Second, the damaged ACL fibers and surrounding tissue encourage vascularization, making it very easy for the augmented portion to adapt once it has sufficient bloodflow. Third, the
augmented portion becomes a "stint", providing the original ACL with protection from additional stress.56

As there is little, if any, association between ligament laxity (which is variable among individuals) and eventual function and symptoms, it is difficult to determine whether one surgical technique is more effective than another. Usually studies of surgery success or failure are measured by the degree of the patient's original performance that he is able to return to following surgery. No one particular surgery technique is preferred over another, according to one author57, therefore several techniques will later be illustrated and described.
The patient with a torn ACL often has the choice of nonoperative or reconstructive correction, particularly depending on the severity of the tear as well as his expectations of returning to an original performance level. If he does choose reconstructive surgery there are several more options that he, and the surgeon, will need to consider.

While a number of reconstructive methods are currently used, the most common are the patellar tendon (bone-tendon-bone) technique and hamstring harvesting, both which will be discussed. Symptomatic results barely differ between methods following acute ACL tears, and in addition, both can be performed openly or arthroscopically assisted. Along with the patellar tendon technique, an alternate method to be discussed, the dual tunnel technique, has been developed which also demonstrates no substantial difference in results.

Often the decision of method utilized is left to the surgeon who will probably choose that which he personally has had the most success with in the past. However he should also consider the patient’s demand of the injured knee. The patellar tendon techniques appear best for early fixation and are preferred for the intense athlete who would like to
return to the sport in a short time. The patient may regain use of the knee in a considerably shorter period of time. On the other hand, for the patient concerned with scarring, the hamstring technique is preferred as more of the procedure can be carried out arthroscopically, avoiding much of the unattractive scarring often associated with knee surgeries.61

Operations are performed with the patient supine, usually with the knee flexed to 90° and supported by a bolster. It should be noted that often the surgeon will choose to leave a stump of the ACL along with its vascularization, which will contribute to the blood supply of the future graft. In addition, with the stump still attached, proper positioning of drill holes for the graft will be ensured.62

The surgeon must take precaution when working in such a small area. Directly posterior to the ACL is another important ligament, the PCL, which should not be disturbed. He should also take care in examining the menisci of the knee, acknowledging any damage which may necessitate additional procedures. In the case of a tear of the menisci, a partial meniscectomy or meniscal repair may be in order.
Patellar Tendon (Bone-Tendon-Bone) Technique

An incision is made on the anterior knee surface, either centrally or slightly medially, extending from 3 cm above the inferior pole of the patella to 3 cm below the superior edge of the tibial tubercle. Once uncovered, the patellar tendon, stretching from the patella to the tibial tubercle, is measured in width and divided into thirds. The central third, preferably 10-12 mm wide, will be the future graft used to replace the ACL.

A rectangular bone block is cut from the distal patella, measuring 25 mm long, 10 mm wide, and 5-8 mm deep. These cuts are continued through the length of the tendon to the site of attachment at the tibial tuberosity. Now another bone block, wedge-shaped this time, measuring 30 mm long, 10 mm wide proximally, 20 mm wide distally, and 5-8 mm deep, is removed from the tibia.

A second incision, approximately 5 cm in length, is made on the lateral side of the knee. The opening will facilitate securing the graft which will be passed around the back of the femur and attached over the top of the lateral epicondyle.

A wedge-shaped drill hole is made from the anterior tibia to the tibial plateau. This drill hole should only be
wide enough for the patellar bone block to pass through on its way to its over-the-top position of the lateral epicondyle. As the patellar block is pulled straight through the drill hole from the tibial end, the tibial block, still connected by the tendon, becomes wedged tightly in the drill hole. The patellar block is then secured to the femur with K-wire as the surgeon checks the knee's range of motion. Once he is satisfied with the proper tension of the graft and also that there are no interferences with the graft, he secures the patellar bone block with a screw and washer. The tibial block is firmly fixed in the tibia, however, it will take 6-10 weeks before the patellar block is fused to the femur, therefore extra precautions should be taken in the patient's activities for that period of time.
Dual Tunnel Technique

The dual tunnel technique is an alternate method to the preceding method. A tendon graft is removed from the patellar tendon in a similar fashion as already discussed, however, in this case the tibial bone block should be rectangular and of the same dimensions as the patellar block.

Although the surgeon will often incise the lateral side of the knee for the securing of the grafts, as in the first procedure, he may also consider assisting the surgery arthroscopically, with only a small opening, avoiding a large incision and preventing future scarring.

A drill hole will be made through the tibia once again and an additional drill hole will be made in the femur, running from its base to its lateral side slightly over the epicondyle. Both will be only as wide as the bone blocks are and neither one will be wedge-shaped, as the blocks will be secured this time by other means.

The patellar block is passed through the tibial drill hole, then is pulled partway into the femoral hole and secured with an interference screw. As mentioned earlier, many surgeons will secure the bone block through a lateral incision approximately 5 cm long, however, the procedure can be assisted arthroscopically instead. Using an endoscope, a narrow tubular instrument, the surgeon can perform the
technique just as effectively but through a much smaller incision.

The knee is checked again to verify it can be fully flexed and extended with no interference, and the tibial block is finally secured within the drill hole by an interference screw.
Hamstring Harvesting

This technique involves a third incision, however especially in the arthroscopically-assisted cases, incisions are small and scarring can be kept at a minimum. A 5-7 cm vertical incision is made 2-3 cm medial to the tibial tubercle. Depending on the condition of the ACL the surgeon must decide whether or not the semitendinosis, which will become the graft, should remain attached at its distal location on the tibia. In cases where reconstruction is necessary, where a complete tear has occurred, the semitendinosis will be detached from its location at the tibia and doubled over for stronger support. This technique will be discussed later.

In cases where only an ACL augmentation is needed, when a partial tear has developed and the ACL simply needs reinforcement, the semitendinosis will be left attached at its tibial location and cut proximally above the knee. A lateral incision, as used in the previous techniques, is made as well.

A drill hole similar to those made previously is drilled through the tibia and sized according to the diameter of the tendon. Inserted into the knee through an arthroscopic portal, a guide wire carrying a suture is used to pull 4 mm Mersilene tape through the tibial drill hole and out past the back of the femur. As the knee is flexed and extended, the
tape is observed for unnecessary movement from its original positioning. If there is excessive movement, the posterior end of the tibial tunnel will be widened.

The tendon is then pulled through the tibial hole and back around the femur. Its free end is then attached to the femur by folding and stapling it with a belt buckle technique.

If the graft has been detached at its tibial location, as in the case of the reconstruction, the semitendinosus is cut above the knee, freeing it from the other hamstring muscles. It is removed, doubled over, and sutured together along its entire length, leaving only a loop at one end. A drill hole is made through the tibia and the same lateral incision will be used. The Mersilene tape will again serve as a test for excursion and any necessary widening of the drill hole will be performed.

Finally, the doubled-over tendon will be pulled through its tibial hole, loop first, and fastened to the posterior femur with a bicortical screw and washer. The distal end of the tendon is folded over and secured with a belt buckle technique.
In all cases of the surgeries, the patient should remain immobilized for a day or two. A brace should be worn and sessions of passive motion should be monitored for several weeks according to the comfort of the patient. Crutches should also be used for several weeks after the patient begins walking again to prevent excessive stress on the substitute ligament as it gradually incorporates itself to the bone.
Although we would like to believe surgery will be the last and most preventive measure of a complete ACL tear, the complications that may follow surgery prove that there is still more to learn of this complication both in and out of sports. Although figures represent most patients returning to their normal daily activities and a good percentage carrying out their sporting fun, many patients will still be reminded of their injury by minor complications that follow, including limited knee motion, patellofemoral pain, and quadriceps weakness. We must remember, however, that surgery prevents many more difficulties than these, such as the loss of use of the knee altogether.

The first of the three common post-surgery complications is limited knee motion, which stems from one or more of the following factors:

- prolonged immobilization during and after rehabilitation
- technical problems originating from the graft placement or tension
- arthrofibrosis occurring in surrounding areas of the condyles
- infection
• RSD (Reflex Sympathetic Dystrophy) which may involve limb atrophy, osteoporosis, hypervascularity (excessive blood flow), and hypersensitivity to pain.

Studies showed that limited motion occurred in 7-32% of the cases while open surgeries and surgeries performed within the first week of injury were the most prominent cases. As discussed earlier, if the swelling of a newly injured knee has not been let to subside (usually for a week or so), the tensioning of the graft may be affected during a reconstruction.

In one particular study following surgery, patients were immobilized for approximately three weeks at 30° flexion, then instructed to wear a brace with a 30° extension stop for 3-5 weeks. One year after surgery an averaged 29% of the patients had a limited knee motion greater than 5° compared to the opposite knee. By immobilizing other patients in full extension for only 10-14 days, results improved considerably. These cases that utilized a patellar tendon graft dropped from 32% to 11% incidence; those utilizing a hamstring tendon graft dropped from 24% to 0% incidence, strongly supporting a shorter immobilization time.

Another option supported by bone researchers has been continuous passive motion immediately following surgery. Other researchers did not support this method, commenting that it had no impact on post-operative rehabilitations.
Within a year after an ACL operation, 19% of patients experience patellofemoral pain which involves knee pain and often tendinitis.\textsuperscript{71} The latter problem can usually be associated with aggressive progressive resistance exercises during the rehabilitation period. Often the pain can be subsided with rest, anti-inflammatory agents, and specific quadriceps exercises.

Quadriceps weakness, strength less than 80% of the opposite leg, affects 65% of patients a year later who have undergone ACL reconstructions.\textsuperscript{72} Surprisingly, however, the majority of these complaints are from patients with patellar tendon grafts, rather than hamstring tendon grafts.

In addition to these complications, patients may complain of adhesions, decreased strength of the extensor muscles, later graft failure, and possible loss of proprioception, certain nervous receptions, of the leg.\textsuperscript{73} These problems are less frequent than those described above, however should still be explained by the surgeon to his patient.
ACL injuries, whether or not they involve an associated meniscal injury, are currently corrected with a variety of different methods, as have already been discussed. Once the preferences of operative or nonoperative techniques have been discussed, it becomes evident that not one or the other approach is preferred except on the basis of the individual's situation, particularly his own level of activity before and after the injury. Statistics throughout the research have indicated that both operative and nonoperative procedures can be extremely successful and there seems to be an optimistic outlook on future research and rehabilitations in both areas. Studies of 256 patients treated nonoperatively were collected to assess the success of current rehabilitation programs. All the patients suffered an ACL injury and several also had associated meniscal injuries. The follow-up time extended 38-67 months, during which time the patients were prescribed a brace, exercised, and attended counseling sessions. As mentioned earlier, the most important criteria when considering surgery is the patient's expectation of activity following the recovery. Statistics have not been found to differ between operative and nonoperative methods.
substantially, therefore, we shall assume these results would be similar if these studies had involved surgery.75

1) 90% of the patients were able to return to their normal activities in both their daily living and at work. However, especially for patients who performed strenuous activity in their job, surgical reconstruction did become a preventive measure in following years.

2) 75% of the patients were able to return to sporting activities upon recovery. It should be noted, additionally, that not all of the 25% not returning had the time or incentive to continue previous activities. Although only 15% of the patients returned to their original activity level experiencing no symptoms, 60% did participate simply by modifying their exercises.

3) Arthroscopy was later necessary for only 12% of the patients, all who experienced a reinjury, specifically a meniscal tear. 20% of the patients followed through with reconstructive surgery due to poor performance of the knee. Not all the patients required reconstruction, rather opted for it in order to improve their performance in work or sports.

4) Unfortunately, a large number of patients still exhibited symptoms at the time of their follow-up. 62% experienced 'giving way', 57% pain, and 36% swelling, however most of these symptoms would recur during periods of
strenuous activity. A small percentage (10-15%) of the patients chose to discontinue high-stress sports such as racquetball, basketball, skiing, football, and ice hockey.

5) Meniscal tears, when occurring singly in an ACL-deficient knee, did not appear to substantially affect the recovery of the knee, however when both menisci were torn, recovery rates were adversely affected. In fact, with both menisci torn, the patient's probability of reconstruction was greatly enhanced. This finding may be rationalized if the responsibility of the menisci is reconsidered. Menisci distribute the intense stress loads to a broader surface so no one designated part of the knee is overworked. While the knee is supplied with two menisci, perhaps the stress load will still be distributed, just not as effectively, over the knee's articular surface, in a case of a single injured meniscus; the other may simply assume more pressure. Once both are affected, weight distribution becomes difficult and surrounding knee structures will feel the impact of every single step, twist, or pull.

6) Reduced symptoms were found to correspond to greater thigh girth, quadriceps strength, and hamstring strength. Evidently, the conditioning of leg muscles served to support much impact the knee received.

7) One study demonstrated improved results in cases where the patients wore a brace during rehabilitation. Unfortunately many patients felt the brace was a hindrance to
their performance, and did not wear it, even when it was prescribed.

8) More frequent symptoms and higher reconstruction rates did seem to correlate to a certain age bracket. Patients particularly in their early twenties were often unwilling to moderate their activities following injury, and, in fact, pushed themselves to higher and higher levels of competition. Probably for this reason those patients demonstrated fewer success stories.

9) Functional results depreciated eventually with time following ACL injuries.
A research paper, and more specifically a master's degree thesis, should primarily demonstrate the student's interest and knowledge of his chosen subject combined with his field of schooling. Medical illustration is a field of study I find quite interesting and challenging for this combination. With the vast amount of research and surgery conducted all the time, I had a great number of subjects to choose from. In addition, the range of illustrative techniques available was almost endless, therefore I did a lot of experimentation. By combining these two areas of interest, I have submitted an informative paper in order to fulfill my requirements for my master's degree.

At the onset of my research, I originally chose sports injuries of the lower extremities as a topic. Information was abundant and so specific, however, that soon I narrowed the topic down to the knee, and finally the ACL, as it was one of the most commonly injured structures of the knee.

All of my information was collected at the University of Rochester Medical Center Library. The books and journals contained detailed current research and surgical techniques on the ACL and its surrounding structures, but again, I chose
to limit my personal studies, keeping in mind my potential audience of this paper, namely the general public. I attempted to keep the information and illustrations descriptive and simplified as many readers would be reading it for their own benefit while considering a future reconstruction themselves.

My first brainstormed ideas for thesis presentation involved MacroMind Director, a computer program that I had recently become interested in. Several original animations were produced demonstrating capabilities of the computer. A cartooned run sequence, some varied text samples, and animated graphs were produced which I had hoped to combine into a fun game-like informational disk. However, I felt that the computer would distract the viewers from any original artwork that I would have scanned in, therefore, the computerized work became a lesser priority.

Sketches were initiated which described three surgical processes. Beginning with descriptive reports of several common reconstructive procedures, I represented the surgeries in several consecutive steps. Once again I considered my audience and limited the sequences to three illustrations, demonstrating the original site of the graft as well as a posterior and one quarter view of the knee. The posterior views demonstrated most clearly the angles and locations of the final grafts. While each graft was depicted firmly attached, by screw or wedge or staple, to the bone,
each tendon stretched from tibia to femur taking over the job of the damaged ACL. One quarter views were carefully chosen in addition in order to confirm the anterior graft attachment as well as provide a slightly lateral view of the graft (the patellar tendon would obstruct the graft in a full anterior view).

With this arrangement my audience would easily decipher which structures would be involved in the reconstructions and realize the final outcomes of the processes. Their attentions would not be complicated by measurements, angles, or tools used, as I assumed that this information would not particularly interest the layman.

Line drawings demanded precise anatomy as well as a bit of imagination. Plastic models of the leg bones were borrowed from instructors and hung or propped in the correct positions then graphite pencil drawings were developed. Anatomy textbooks were consulted for the proper placement of ligaments, muscles, and drill holes that were described in the journals. The most difficult task became the depiction of the ligaments underneath the surface of the bone. With some creativity I twisted and bent the grafts as I could imagine they would appear around and within the bone structures.

From the very beginning of the illustrating process, the media utilized and how it was used were some of my primary concerns in the incorporation of the thesis. Of course, I
preferred a medium that wouldn't require a great deal of
time, and, of course, one which I felt very competent with.
There was, in fact, a time restraint for the thesis to be
finished and I probably could not afford many complications
in order to produce my best work. Airbrush with detailed
watercolored structures was an early consideration of mine,
however, I felt that there were other media that I utilized
more time-effectively. Pen and ink was a medium that I
enjoyed very much, but after studying current journals, I
sensed that most of the work appeared in pen and ink already.
One of my goals was to produce original illustrations that
perhaps represented improvements over previous work,
therefore this medium, as well as half-tone, was rejected.

Full-color illustrations were eventually produced using
an interesting combination of media. Once the pencil
drawings were manipulated and completed on tracing paper,
then copied to the final charcoal paper, a diluted white
acrylic paint was applied to the areas which would later
represent ligaments. Once dry, the paint was lightly sanded,
adding some texture, in order that I could draw on it.
Eventually, when pencil was applied to these areas, they
appeared more opaque, attracting the viewer's attention there
instead of to bone or muscle structures. The process of
colorizing took several weeks and often demanded very
intricate attention, such as in the areas of screws and
staples. Berol Prismacolor pencils were used for this
process. Various colors including terra cotta and shades of
blues produced the muscle, tendon, and ligament structures, while brown and yellow shades accented the bone. Wherever possible, particularly on the bone, the charcoal paper was allowed to show through in order to incorporate the background color more effectively.

Lighting was controlled at all times in order to produce realistic bones which looked similar between the three surgeries. The viewer could still flip from one surgery to another and comprehend the status of each process.

Finally, after much consideration, each step of each surgery was highlighted with a tuscan red pencil. Crimson pastel powder was added to most of the backgrounds to give the works considerably more depth, in addition. Labels were applied with vinyl lettering and each surgical sequence was matted.

With the surgeries completed, I felt it was necessary to demonstrate the correct positioning and points of attachment of the ACL, particularly for the layman who may not realize the importance of this valuable ligament. Utilizing models and textbooks as well as my own mirrored leg as a reference, I illustrated first an anterior view of the ACL in action, limiting the forward pull of the tibia. Next, a side view of the knee was designed in which part of the femur had been cut away. In this manner, the attachment of the ACL to the back side of the femur could be demonstrated. Both illustrations
were created with the same technique and media as discussed before.

The other aspect of a reconstruction I wanted to demonstrate was the initial diagnosis of a torn ACL. There are several tests performed in order to assess the damage to the ligament, however, I chose three in particular that appeared from research to be the most reliable and cost-effective. Originally I had planned to illustrate these tests in colored pencil also, but as some of my recent extracurricular work had involved some photography, those interests extended into my thesis work. Using black and white film (135 mm TMX) I photographed the right leg in the various positions manipulated during a routine diagnosis. I developed each pose into a photograph approximately 8 by 6 inches and scanned them into Adobe Photoshop 2.5.1 on the computer in order to manipulate them. Each photograph was colorized utilizing the duotone process in order that the collection would match similarly the colors of the completed surgery illustrations. The images were then transferred to Adobe Illustrator 3.1 where the blue arrows were added with the pen tool.

These test procedures were printed out on a di-sub printer and matted within the charcoal paper. Sketches were then produced on tracing paper, each representing the potential dislocation of the joint in the case where an ACL was injured. With the sketches transferred to the paper, pen
and ink line drawings were made of these dislocations beneath their corresponding photograph image. Finally, the entire collection was matted.

At the beginnings of my research of the ACL I had proposed to create original artwork which would be a tool in the education of a common sports injury that many athletes do not completely understand. Through my research and illustrations I feel I have submitted an informative yet simplified paper which the layman can read and appreciate. In addition, the thesis has broadened my knowledge of both the applied medical approaches and artistic techniques. I certainly hope that, for the next reader, this thesis can be worth half the knowledge that I have gained by producing it.
GLOSSARY

arthrofibrosis: excessive fibrous tissue development around the joints.

arthroplasty: surgery, typically plastic surgery, of the joints.

arthroscopy: the examination of a joint using an arthroscope, an instrument designed for interior analysis.

articular cartilage: a hard, pliant material which forms a smooth layer over the surface of the long bones in the body and constitutes, in part, the joints.

collateral ligament: a secondary stabilizing ligament of the knee, stretching from the femur to the tibia.

condyle: the rounded protrusions at the ends of the long bones of the body, in particular.

epicondyle: the protrusion over the condyle.

iliotibial tract: an expansive tendon running from the illium to the tibia.

ischemia: depletion of blood to a part of the body due to an obstruction or constriction.

meniscectomy: the removal of a meniscus.

meniscus: the crescent-shaped padding of fibrocartilage at the tibial plateau; occurs in pairs.

notchplasty: a surgical widening between osseous protrusions to allow for improved visualization of an affected area.
patellar tendon: a tendon extending from the patella to the tibia.

proprioception: nervous perception by the proprioceptors of the body which receive stimuli within the tissues (particularly within muscles and tendons which deal with movement).

semitendinosis: a hamstring muscle at the posterior upper leg.

synovectomy: removal of the synovial membrane of the knee, often in the treatment of rheumatoid arthritis.

tibial tubercle: the slight projection near the proximal end of the tibia where the patellar tendon attaches.

tuberculosis: an infectious disease leading to the formation of tubercles and necrosis of the tissues.

valgus: outwards from the center of the body.

varus: inwards towards the center of the body.

Vitallium: a cobalt-chromium alloy used for dentures, prostheses, and surgical instruments.

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11Ibid., p. 6.
12Ibid., p. 6.
13Ibid., p. 6.
14Ibid., p. 7.
16Ibid., p. 687.
17Ibid., p. 687.
18Ibid., p. 688.
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20Ibid., p. 691.
22Steadman et al., p. 685.
24Ibid., p. 627.
25Johnson et al., p. 671.
26Larson et al., p. 12.
27Ibid., p. 566.
28Ibid., p. 38.
29Ibid., p. 37.
30Ibid., p. 534.
31Ibid., p. 505.
32Ibid., p. 494.
33Ibid., p. 494.
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35Ibid., p. 505.
36Ibid., p. 495.
37Ibid., p. 496.
38Ibid., p. 506.
39Ibid., p. 506.
40Ibid., p. 507.
41Ibid., p. 507.
42Ibid., p. 86, 87.
43Ibid., p. 83-86.
44Ibid., p. 87, 88.
46Ibid., p. 104-106.
47Ibid., p. 115-118.
48Ibid., p. 109, 110.
49Ibid., p. 543.
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51Ibid., p. 492.
52Ibid., p. 533.
53Ibid., p. 533.
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63Ibid., p. 546-552.
64Ibid., p. 552-554.
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68Ibid., p. 672.
69Ibid., p. 672.
70Ibid., p. 672.
71Ibid., p. 672.
72Ibid., p. 673.
73Steadman et al., p. 686.
74Larson et al., p. 541.
75Ibid., p. 541, 542.