Martha M. Murray
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Braden C. Fleming
Editors

The ACL Handbook

Knee Biology, Mechanics, and Treatment

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To our patients, who motivate us every day to put our best effort toward finding improved treatments for ACL injury.

Preface

Emily was driving toward the basket, a move she had done a 1,000 times before. She went up for the shot, and upon landing, her knee gave way. She felt a shifting in her knee microseconds before she heard a "pop." After dropping to the court and grabbing her knee, she was carried off the court by her concerned coach and trainer. They wrapped her knee in ice packs and sent her to see her doctor in hopes it was not a devastating ACL injury. Her visit with me, an Orthopedic surgeon, would confirm a diagnosis of an ACL tear – a seeming death sentence for so many athletes.

Upon hearing her diagnosis, her questions were numerous and understandably so. "Will I play again?" "Will I be as fast as I was before my injury?" Her most pressing question was "When can I get back on the court?"

ACL injuries affect the lives of hundreds of thousands of people every year. The patients who sustain these injuries and the families, teammates, coaches, and healthcare providers, who care for these patients through their injury and recovery, all have questions related to this injury. Currently, we know the answers to some of the questions. For the most part, we know that patients can get back to sports after ACL injury, and with proper training, their performance can be where it was before the injury. Other questions we do not know the answers to, such as who will develop arthritis after their ACL injury and how that can be prevented.

Great work is going on in this field in an effort to prevent injury and to improve treatment options for our ACL-injured patients. In this book, we attempt to distill all of this information to make the science behind the treatment of ACL injuries more understandable. As you will see, much has been learned in this field, but there is substantial room for improvements.

Emily went on to have ACL reconstruction surgery and is back playing basketball. She underwent an extensive period of rehabilitation, and her mom feels she is playing even better now than before her injury. But still we wonder – can we someday return the joint to a more normal status? Can we prevent arthritis in these patients as they get older? Can we get the ACL to heal after a tear, rather than replacing it with a tendon graft? When given the right biological signal, could

ligament repair be a better long-term solution for Emily and individuals like her? These questions keep us, and many other doctors and researchers, working toward an improved understanding of the ACL and its response to injury. We hope you enjoy the material presented here, and we also hope the work in this area will lead us to better solutions for the treatment of ACL injuries, solutions which will involve repair and regeneration of this crucial ligament instead of its replacement.

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Part I
ACL Injury: The Clinical Problem

Chapter 1
ACL Injury Epidemiology

Patrick Vavken and Martha M. Murray

The book you are about to read focuses on ACL tears, why they do not heal, how to best treat them today, and what may be the best ways to treat them in the not too distant future. ACL tears have gained a fixed place in common knowledge, not only because of the devastating effects they have on the careers of sports idols but also because of the same effects they may have on friends and family members who may have suffered from such an injury (Fig. 1.1). But despite this "popularity" and the considerable amount of research done in this field, there are still a few very basic questions that deserve attention.

First and foremost, who is likely to tear his or her ACL? Identifying the risk factors for injury may help us focus our attention on individuals who are at risk, help them avoid high-risk situations, or direct them to preventative treatments. There are other important questions as well. For example, if a person has an ACL tear, is he or she more likely to tear the other ACL too? How many ACL tears are there in a given year? This will tell us how many knee surgeons we need and how many ACL injuries the medical system needs to be able to cope with. What happens after an ACL ruptures and how are ACL tears currently treated? Which procedures have the highest success rates? Which procedures do not work at all, and which people are at risk of re-tearing their ACL? All these questions, and many more, are of interest not only

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Fig. 1.1 High school women's lacrosse is one of the sports where athletes sustain ACL tears. Young women are at particular risk for this injury

for patients and their families but also for physicians, physical therapists, certified athletic trainers, insurers, and coaches.

Epidemiology is the study of the distribution and determinants of health and disease which enables us to answer many of the questions listed above. The most important tools for epidemiologists are surveys and large databases that collect data on a wide range of patients or subjects at risk to deduce effects from observed trends and commonalities.

Where Does the Epidemiology Data Come From?

Traditionally, epidemiologists have relied on the recollection or documentation of individual physicians or departments for data on ACL treatments and their outcomes, leading to broad statements such as "100,000–400,000 tears in the USA per year" or "one every 6 minutes in Germany." Naturally, such data come with a high chance of bias (an error consistent with a systematic deviation from the truth) and reports were frequently in conflict. Also, since it is not unusual that a year or more passes between a scientific study and its publication, such data are often outdated. Recently, there has been a major movement towards evidence-based outcome documentation with large prospective cohort studies and patient registries. Physicians at academic institutions in the United States have started multicenter studies to collect patient data independently and systematically, for example, the MOON (Multicenter Orthopedic Outcomes Network) [1, 2] and MARS (Multicenter ACL Revision

Study) [3, 4] cohort studies. The MOON group has studied over 2,700 patients undergoing ACL reconstruction, with 85 % follow-up at 6 years postoperatively.

Registries are more common in the Scandinavian countries [5–8]. With their socialized health-care system, all ACL treatments are recorded and can be linked to other patient data (age, gender, etc.) via social security numbers. To date, these registries have systematically collected data on tens of thousands of ACL patients. Similar endeavors have been implemented with success, for example, in Denmark or Italy. While these registries can enroll a large number of patients, one of the drawbacks has been difficulty in following the patients postoperatively because of the high rate of patients lost to follow-up. Nonetheless the registries are most useful for generating epidemiologic information about who is getting ACL tears at this time. In the United States, such registries are being set up but are run by insurances or health-care companies. For example, Kaiser Permanente has a registry of approximately 5,000 ACL patients. Naturally, conflict of interest may be an issue in a registry run by a commercial, for-profit company.

How Often Do ACL Tears Happen?

A good first question to start looking at the epidemiology of ACL injury is the frequency of ACL tears. In epidemiological studies, this is usually given as incidence, or the number of ACL tears per 1,000 people in 1 year (for all calculations, we assume the United States population is 320 million people). All additional risk factors set aside, current estimates are that 1–10 in 1,000 people tear their ACL per year. Assuming the current United States population is approximately 320 million, this translates into 32,000–320,000 ACL tears in the USA per year. Others have estimated this number to be as large as 400,000 per year [9]. For comparison, a year has roughly 10,000 h (8,736 h), which means there are roughly 3–40 ACL tears per hour in the United States. Official registries from other countries support these numbers: in Scandinavia (population = 25 million), there are two ACL tears every hour, and Germany (population = 82 million) and Switzerland (population = 8 million) each have one ACL tear every six minutes and every hour, respectively.

Who Tears an ACL?

ACL tears most frequently occur in situations of a valgus or anterior stress to the extended knee (Fig. 1.2) but can also occur during hyperextension or extreme internal rotation of the tibia. While this is usually associated with the image of a high-impact trauma, such as those seen in professional football or basketball, it is very important to realize that 80 % of all ACL injuries are “noncontact” injuries. These

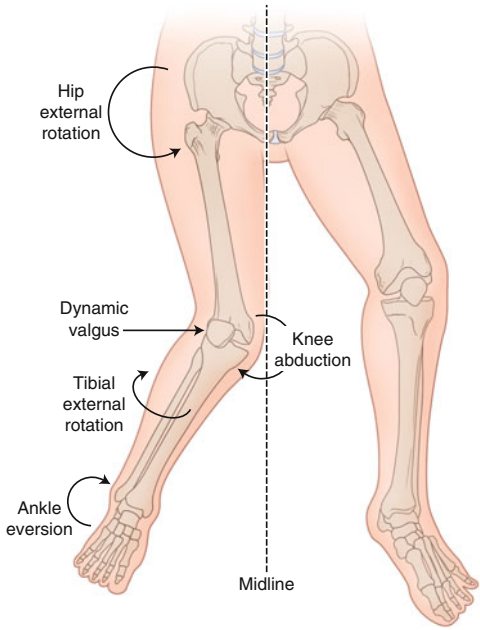

Fig. 1.2 Typical knee position for ACL tear. The ACL is most stressed in a position of combined valgus, adduction, and internal rotation – or a knock-kneed position with the foot apart and the toes turned in. Such a position is frequently seen during cutting or pivoting or when kicking a soccer ball

are injuries that occur when the player is not near another player, and they typically occur when the player is cutting, pivoting, or abruptly stopping. The exact mechanism of such noncontact ACL tears includes poor knee positioning (e.g., extension of the knee during landing) and a strong, unopposed quadriceps contraction. By identifying risk factors for ACL injury, it is hoped to develop individualized prevention programs that address muscle imbalances or poor positioning of the limb relative to the body to help minimize the incidence of ACL injury, especially for the noncontact-type injuries.

ACL Tears in Female Athletes

There is a higher risk of ACL injuries in females than in males. Depending on additional risk factors, which will be discussed later in this chapter, the female to male ratio of ACL tears has been reported to range from 2:1 to 8:1, although most evidence suggests this ratio to be closer to 3:1 (Fig. 1.3) [11]. A large number of gender-specific risk factors have been proposed and assessed to explain this difference. Proposed risk factors have included (1) decreased room for the ACL at the end of

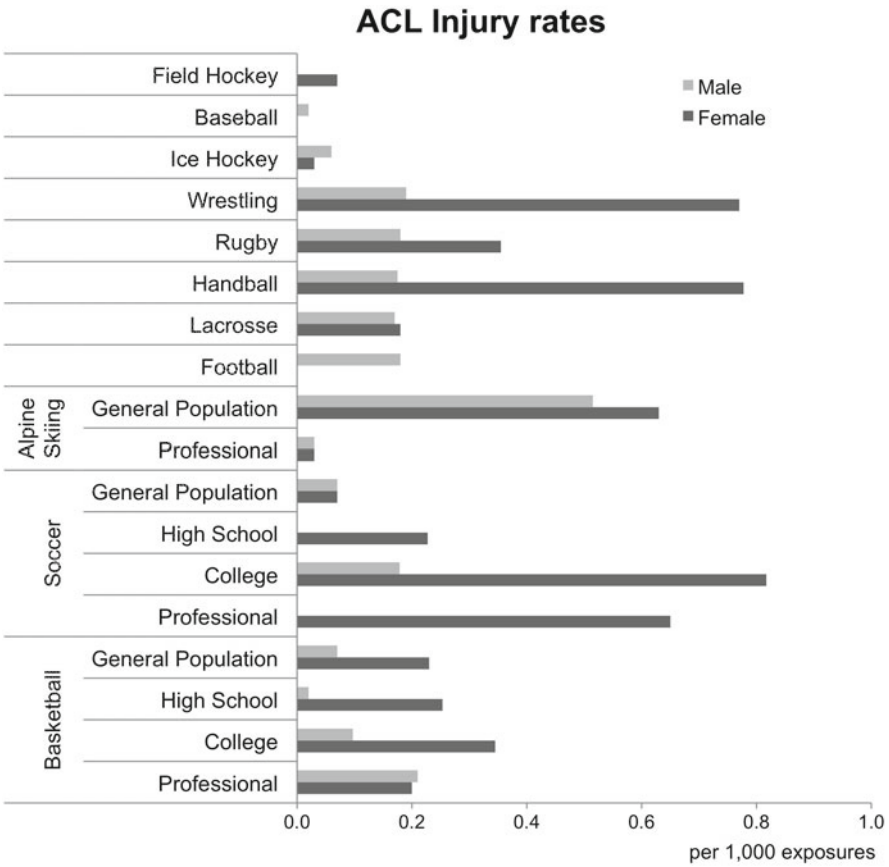

Fig. 1.3 Male–female ratio. This figure shows the ACL injury rates (per 1,000 exposures) for men and women for specific sports. Typically, the rates of injury in women are higher than the male rates at a ratio of 3:1–8:1, depending on the sport participated in (Reproduced from Renstrom et al. [10], with permission from BMJ Publishing Group Ltd.)

the thigh bone (decreased intercondylar notch size), (2) influence of the menstrual cycle (although multiple studies have shown different phases to be at risk, so this is not clear), and, most importantly, (3) development of knee valgus during impact on landing (the knees drop toward each other – Fig. 1.4). Injury prevention programs have been shown to decrease the risk of ACL injuries, particularly for women athletes, by teaching them to 1) land in a safer, non-valgus position, 2) to focus on keeping the knees over the toes when landing, 3) to land softly on the toes rather than the whole foot, and 4) to land on two feet when possible (see prevention section on page 10 for links to specific programs).

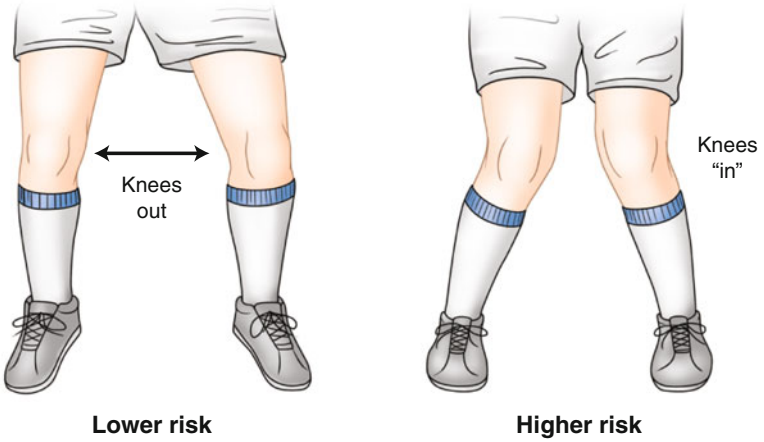

Fig. 1.4 Landing mechanics. One reason for the higher rate of ACL tears in females compared to males is the landing mechanism after jumping. Males usually land with the knees apart and above the feet ("lower risk" position), whereas females land in a "knock-kneed" or valgus position close to full extension leading to excessive stress on the ACL ("higher risk" position). Improving landing position and mechanics is a very simple yet effective way to prevent noncontact ACL injuries

Sports-Specific Risks of ACL Tears

Another important group of risk factors is professional or recreational exposure to different types of sports. Higher-risk activities include those that involve high running speeds, abrupt changes of speed and/or direction, and jumping and landing. The combination of these higher-risk sports with other risk factors such as lack of experience, lack of education for proper technique, and inadequate equipment results in fairly specific risk patterns for a number of sports (see Fig. 1.3).

The four sports that are most noted for the danger they pose to the ACL are alpine skiing, soccer, basketball, and football. Alpine skiing is an excellent example for the role of experience in the risk of ACL injury. Recreational skiers have one of the highest risks for ACL injury, but the risk for "expert" skier is 16 times lower and actually the lowest in the high-risk sports even though the expert skier spends more time on the slopes (i.e., higher exposure). Technical skill and a better general fitness condition are most often quoted as the reasons for this. Interestingly, skiing, when done by experts, represents the rare occasion in which no gender differences are seen [12]. The only other sport to have shown no gender difference in ACL injury is lacrosse [13].

Large studies have been conducted on ACL injuries in soccer and basketball, showing ACL injury rates of 2.8–3.3 % for females and of 0.7–1.2 % males, consistent with the threefold higher rate in females mentioned above [13, 14]. As opposed to skiing, studies showed that the risk of sustaining an ACL tear is higher for professional athletes than it is for recreational athletes in soccer and basketball. Further analysis of ACL injuries in soccer and basketball revealed a plethora of potential risk factors, including the above-mentioned motion patterns, but also the type of turf, the type of floor, or the type of shoes worn.

Natural grass fields are associated with lower rates of knee, ankle, and foot injuries than artificial turf. A number of studies have suggested that shoe design could influence ACL injury risk. The "release coefficient," which is the force-to-weight ratio of the shoe and surface interaction, has recently gained attention. Briefly, an optimal shoe design will have minimal rotational friction – which would reduce rotational stress on the leg – and maximal translational friction, to allow safer stopping and subsequently fewer ACL injuries. Heidt et al. tested 15 different types of shoes and found that 73 % were "unsafe" or "probably unsafe" [15–17]. Unfortunately no specific shoewear recommendation could be deducted from these studies.

Age-Specific Risks of ACL Tears

One issue that deserves special attention is the question whether age, specifically young age, is a risk factor for ACL tears. Over the past few years, there has been an approximately 400 % increase in ACL injuries in children and adolescents, and it is currently estimated that 50 % of all patients with an ACL tear are between the ages of 15 and 25 (Fig. 1.5). In women, the peak incidence of ACL injuries occur in the 15- to 19-year-old age group [18, 19]. Many consider this counterintuitive, particularly given the old adage that young bones are more flexible than older ones. There has been much stipulation and research as to the causes for this dramatic rise in pediatric ACL injuries. Some suggest a heightened attention to this type of injury has led to a higher rate of detection, with no real change in injury rates.

Another possible reason for this increase is a change in leisure-time activities for middle and high school students. Currently, about 45 million children are participating in organized teams in competitive sports, starting at ages as young as 6 years. Making the soccer or football team is associated with a considerable training load during a vulnerable time in musculoskeletal growth. While participation in sports has many benefits for children and adolescents, some practices involve repetition of fairly narrow groups of motions, leading to an imbalance in the development of muscle strength and joint flexibility. These imbalances lead to excessive strain on ligaments such as the ACL and predispose them to injury.

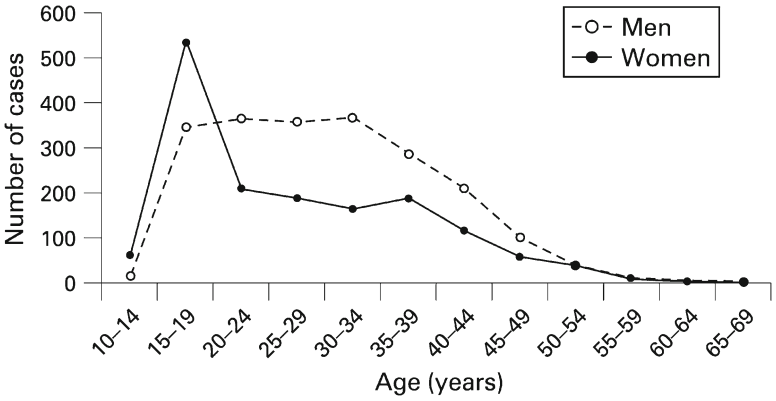

Fig. 1.5 The effect of age and gender on ACL injury rates. This graph shows the distribution of patients in the Norwegian National Knee Ligament Registry by age and gender (Reproduced from Renstrom et al. [10], with permission from BMJ Publishing Group Ltd.)

Knowing the Risk Helps in the Prevention of Injury

Describing these risk factors allows us to identify individuals at increased risk of ACL tears. Risk factors can be reliably used by doctors, parents, and coaches to identify players who might be more at risk for an ACL tear because of their muscle development or limb alignment. The benefit of identifying high-risk individuals is that a number of simple exercises have been developed and assembled to create highly effective ACL injury prevention programs (Fig. 1.6). Such programs consist of simple balance board and postural training that typically require 30 min twice a week, but recent evidence has shown that for every 40 high school students enrolled in such programs, 1 ACL tear can be prevented. And after all, the most effective treatment for any disease is its prevention.

Excellent descriptions of such programs, including pictures, background information, and physician information, can be found online at the Children's Hospital Boston webpage (http://childrenshospital.org/cfapps/research/data_admin/Site2226/mainpageS2226P9.html) or the PEP program website (http://smsmf.org). The International Federation of Football Association, FIFA (Federation Internationale de Football Association), has endorsed a warm-up and exercise program to reduce ACL injury, called FIFA 11+ (see Fig. 1.6). The program can be downloaded from the Internet on the FIFA website (http://f-marc.com/11plus/) and has been shown to be effective in reducing ACL tears [20, 21] even in sports other than soccer, for example, in male, elite basketball players [22].

Fig. 1.6 ACL prevention programs – FIFA 11+. The International Federation of Football Association published this training program to prevent noncontact ACL injury (http://f-marc.com/11plus/). Scientific studies have proven its effectiveness for soccer players and in other sports such as elite basketball (see text for details)

How Many Surgeries Are Done Each Year for ACL Injuries?

How about those ACL injuries that cannot be prevented? For the active patient, the current gold standard of treatment is ACL reconstruction. Current estimates are that about 100,000–400,000 ACL surgeries are done per year in the USA alone [18, 19]. The Statewide Planning and Research Cooperative System (SPARCS, www.health.ny.gov/statistics/sparcs/) database from the New York State Department of Health lists approximately 7,000 surgical ACL surgeries per year in the state of New York, which corresponds to 35 ACL surgeries per 100,000 people in the state. If this rate were similar across the USA, this would correspond to 112,000 surgeries in the USA each year. The national registries from Scandinavia show similar numbers with ACL reconstructions of 34 per 100,000 inhabitants in Norway, 38 per 100,000 in Denmark, and 32 per 100,000 in Sweden.

The severity of an ACL tear is further illustrated by the high number of concomitant injuries. Only one-third of the ACL treatments in New York found an isolated ACL tear, while the other two-thirds of patients had concomitant injuries to the same knee. Thirty-two percent of all patients also required treatment of a meniscal injury. Nineteen percent had meniscus damage combined with further problems, such as collateral ligament sprains or cartilage impact damage [23, 24]. In Denmark, 40 % of the roughly 2,000 patients treated annually for ACL tears had a concomitant meniscus injury, and 55 % needed treatment of a cartilage injury [23, 24]. Similar numbers are reported for Sweden, Norway, Germany, and Switzerland [23, 24].

If I Have Had One ACL Tear, What Is My Risk of Getting a Second ACL Tear?

If you have had an ACL tear, are you more at risk for getting another ACL tear than someone who has never had a tear? The short answer is "yes." As we have seen in the section above, the baseline risk for an initial ACL tear is 35 out of 100,000, or 0.035 %. However, once you have had an ACL tear, the risk of tearing your other ACL within the next 2 years is reportedly between 3 and 23 % [2, 25]. Since this range is quite extensive, one large, high-quality study assessed the risk of contralateral ACL injury over 5 years after an ACL tear and reported that the risk was in the range of 8–16 % [26].

All these values are much higher than the risk for the first ACL tear, suggesting that those individuals who tore their ACL once are at a higher risk of tearing the other one, too. This may be due, in part, to a return to high-intensity, high-risk activities such as participation in cutting and pivoting sports seems to predispose the contralateral ACL to injury. This is also well illustrated by the fact that in those patients whose ACL tears are treated conservatively, that is, those advised to avoid contact or high-risk sports, the contralateral ACL tear risk is only around 1 %.

Other risk factors, including major differences in limb strength at return to sport, are also likely to play a role. A number of additional risk factors, including anatomy, early return to sport, and even familial factors, have been examined, but none have been directly associated with the risk of tearing the contralateral ACL after a primary ACL rupture. Even gender was not shown to have an association with a heightened risk.

The risk of re-rupturing a surgically treated ACL is about 6 % (2–8 %), that is, only half the risk of tearing the "other," contralateral ACL after ACL treatment [2]. Most of these graft ruptures occur within 12 months after surgical reconstruction. Thus, during this first year, the risk of re-rupture can be as high as the risk of a contralateral injury (12 %) [2]. One study looking at 612 patients with torn ACL grafts found that, unlike the first ACL tear, only 5 % were due to a noncontact injury [27].

Proposed risk factors for ACL re-ruptures include neuromuscular factors, the biochemical environment, age, and the level of activity postoperatively. As far as neuromuscular factors are concerned, since the standard ACL reconstruction replaces the torn ACL with a tendon graft, there is no functioning intrinsic innervation and therefore no dynamic feedback loops. One of these feedback loops, the reflective activation of the hamstrings to prevent forward translation of the tibia, has been shown to protect the ACL [28]. If this dynamic feedback loop is interrupted, the hamstrings are no longer signaled to help the ACL when it is stressed, and thus, the risk of ACL injury is increased. For the biochemical environment, an earlier ACL injury and surgery also alters the biochemical balance of the knee joint through inflammation, which has been suggested to affect ACL graft healing and longevity.

Both age and graft selection have also been shown to affect rates of ACL tears, with younger patients having higher graft failure rates and those patients having an allograft reconstruction also having higher rates of graft failure [29]. These factors have been found to be multiplicative. For example, a 14-year-old with an allograft (i.e., tendon obtained from cadaveric donor) ACL reconstruction has a 22 % chance of tearing his/her graft, while the same patient has only a 6.6 % chance of tearing the graft if it is an autologous graft (i.e., tendon obtained from self). In contrast, a 40-year-old patient has only a 2.6 % chance of tearing his/her allograft and only a 0.6 % to 1 % chance of tearing the autograft (Fig. 1.7) [29].

The Cost of ACL Injury

During recent years the scope of epidemiology has expanded to include the economics of health care. The days of abundant financial resources for health care, if they ever existed, are long gone. Costs and cost-effectiveness have become a central issue in the provision of current and the development of new treatments. Musculoskeletal disease, including ACL injuries, is under particular scrutiny since, problems of the skeletal apparatus can turn into a lifelong hindrance and diminish quality of life and ability to work.

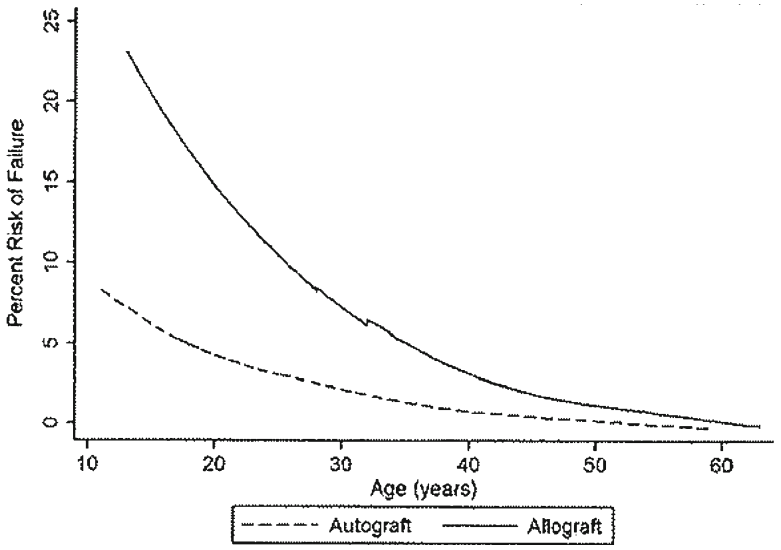

Fig. 1.7 Age-specific ACL reinjury rates. This figure shows the chance of re-tearing an ACL, after ACL reconstruction with one's own tendons (autograft) or with donor tendons (allograft) at different ages. The risk of re-tearing is higher with a donor tendon reconstruction, but this difference reduces with age, as does the overall risk of reinjury (From Kaeding et al. [30], copyright © 2010 by (Sage Publications), reprinted by Permission of SAGE Publications)

The cost of ACL surgery depends on a number of factors. The type of graft that is used is associated with different costs for procurement and different procedure lengths, which in turn affects costs. While there is considerable geographical variation in these costs, an autograft ACL reconstruction (where the patient's own tendons are used) can be estimated to cost about $5,000–$6,000; an allograft ACL reconstruction (where a cadaver or donated graft is used) is about $1,000 more expensive [31, 32]. Among the autografts, hamstring grafts have been shown to be less expensive than patella ligament grafts, because of less operating room time and slightly better functional outcomes [32]. However, for the assessment of medical treatments, cost analyses are not as useful as assessing cost-effectiveness. In addition to the differences in associated costs among the different ACL graft types, there are also differences in their effectiveness. These differences in effectiveness can be expressed in various forms, such as the risk of re-tear or subjective satisfaction of the patient, but the most appropriate way is a formal test using a quality-of-life (QoL) assessment instrument and multiplying this QoL with the number of years the graft is likely to last. This results in the so-called quality-adjusted life years (QALY). Based on earlier studies, hamstring grafts cost about $5,300, bone-tendon-bone grafts about $5,600, and an allograft about $7,000. Thus, hamstring grafts are the least expensive graft type and are the most effective in terms of QALY.

The costs associated with problems that occur during or after ACL surgery are less well documented. An infection in the knee joint has been estimated to produce

additional cost of $9,800 (range $5,000–$30,000). Fortunately, this complication is relatively rare after ACL surgery (less than 1 % of the time). Joint stiffness after an ACL reconstruction will require up to $3,000 in an effort to treat (range $0–$9,000). Revision procedures are even more complicated, riskier than primary surgery because of the tissue changes, scarring, changes in anatomy, the need to remove old implants and fixation devices, and the, now, limited availability of autologous grafts and healthy bone to place them into. Thus, revision surgery is more expensive than primary surgery. If a revision is needed, additional costs of about $20,000 ($14,000–$51,000) should be expected [32]. Naturally, the costs for complications have large variability, depending on how serious these complications are. The rates of full-blown revision for ACL surgery at this time are between 0.7 and 9 %, including the factors outlined above, such as re-rupture or inadequate graft placement or fixation.

Conclusion

ACL tears are a frequent injury with increasing incidence. A number of risk factors, such as female gender or specific types of sports played, predispose some individuals to ACL injury; however, there are modifiable risk factors, which can help to mitigate this risk. Interestingly, the rate of ACL tears seems very stable across a number of countries, as are the high rates of additional injuries that occur in conjunction with ACL tears.

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Chapter 2
History of ACL Treatment and Current Gold Standard of Care

Martha M. Murray

ACL injuries are increasingly common, with estimates as high as of 400,000 patients each year in the United States sustaining this injury (in comparison with 120,000 patients undergoing hip replacement surgery) [1]. The ACL injury is important, not only due to the number of people affected by the injury but also because of the sequelae of the injury. The ACL does not heal on its own, and as a result, many methods have been designed to treat the ACL-injured knee. However, even our gold standard of treatment, ACL reconstruction, cannot prevent the premature onset of arthritis for patients with ACL injuries. This is worrisome for those of us who care for patients with ACL injuries, and as such, we are extremely interested in finding improved solutions for people with ACL injuries.

There has been a great deal of work done over the past two centuries regarding the diagnosis and treatment of the ACL. We will briefly review some of the highlights that seem most relevant to these injuries and those that give us hints of what might work better. Certainly, any work in this field "stands upon the shoulders" of these wonderful physicians and scientists who have laid a great foundation for future studies.

The earliest reports of ACL injuries largely relied on the history and physical examination of the patient, two areas which remain critical to the accurate diagnosis of this injury today. The first identification of the ACL was attributed to Claudius Galen (150 A.D., Fig. 2.1) who cared for the gladiators and likely had the opportunity to visualize the ACL through gashes in the knee. In 1845, Amedee Bonnet of Lyon reported that patients who heard a snap and developed swelling and loss of function in the knee would most likely have a ligamentous injury, including ACL injury. Thirty years later, Georgios Noulis from Greece performed a series of cadaver studies where he found that forced anterior subluxation of the tibia could

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Fig. 2.1 Claudius Galen, b. 129 A.D., d circa 200 A.D. Galen was a physician for the gladiators in Rome and is credited with the initial observation of the anterior cruciate ligament and its traumatic injury (From The Wellcome Library, London)

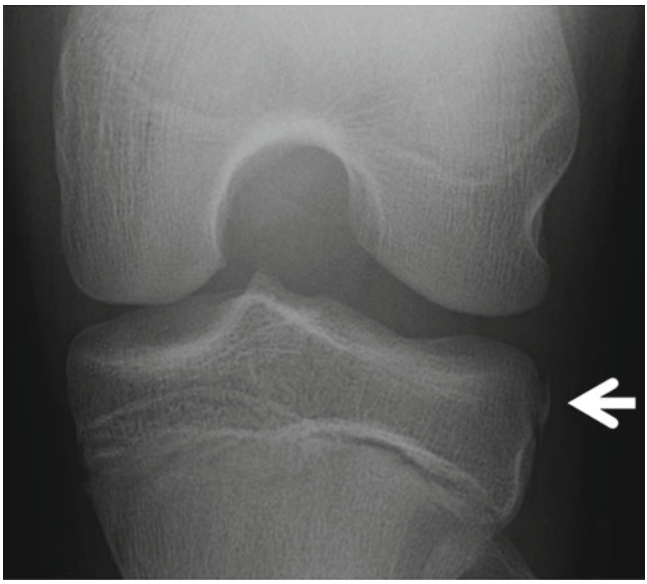

Fig. 2.2 X-ray appearance of a Segond fracture. In 1879, Paul Segond recognized that patients who had a small avulsion fracture off the anterolateral tibial plateau (*arrow*) typically had an ACL tear

cause an ACL rupture, and he described a test very similar to the Lachman test used today for diagnosing a tear of the ACL. After radiography started to become more available in 1879, Paul Segond recognized that patients with a small avulsion fracture off the anterolateral tibial plateau (now called a Segond fracture, Fig. 2.2) typically had an ACL tear. The history, physical exam, and x-ray findings were all critical to the diagnosis of patients with ACL tears.