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10 Year Outcomes and Risk Factors after ACL Reconstruction: A MOON Longitudinal Prospective Cohort Study

MOON Knee Group

Abstract

Background—Long-term individual prognosis and risk factors for quality of life and disability following anterior cruciate ligament (ACL) reconstruction remain unknown.

Hypothesis/Purpose—Our objective was to identify patient-reported outcomes and patient-specific risk factors from a large prospective cohort at a minimum 10-year follow-up after ACL reconstruction. We hypothesized that meniscus and articular cartilage injuries, revision ACL reconstruction, subsequent knee surgery, and certain demographic characteristics would be significant risk factors for inferior outcomes at 10 years.

Study Design—Prospective longitudinal cohort study

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Methods—Unilateral ACL reconstructions were identified and prospectively enrolled between 2002 and 2004 from 7 sites in the Multicenter Orthopaedics Outcome Network (MOON). Patients pre-operatively completed a series of validated outcome instruments, including the IKDC, KOOS, and Marx activity rating scale. At the time of surgery, physicians documented all intraarticular pathology, treatment, and surgical techniques utilized. Patients were followed at 2, 6, and 10 years post-op, and asked to complete the same outcome instruments that they completed at baseline. Incidence and details of any subsequent knee surgeries were also obtained. Multivariable regression analysis was used to identify significant predictors of outcome.

Results—A total of 1592 patients were enrolled (57% male; median age 24 years). Ten-year follow-up was obtained on 83% (1320) of the cohort. Both IKDC and KOOS scores significantly improved at 2 years and were maintained at 6 and 10 years. Conversely, Marx activity level scores dropped markedly over time, from a median score of 12 points at baseline, 9 points at 2 years, 7 points at 6 years, to 6 points at 10 years.

The patient-specific risk factors for inferior 10-year outcomes were lower baseline outcome scores, higher BMI, smoker at baseline, having a medial or lateral meniscus procedure done prior to the index ACL reconstruction, having a revision ACL reconstruction, lateral meniscectomy, grades 3–4 articular cartilage pathology in the medial, lateral or patellofemoral compartments, and having any subsequent ipsilateral knee surgery following the index ACL reconstruction.

Conclusions—Patients are able to perform sports-related functions and maintain a relatively high knee-related quality of life 10 years after ACL reconstruction, although activity level significantly declines over time. Multivariable analysis identified several key modifiable risk factors that significantly influence outcome.

Key Terms

anterior cruciate ligament; ACL reconstruction; follow-up; outcomes; IKDC; KOOS; Marx; revision ACL reconstruction; meniscus; articular cartilage; subsequent surgery

INTRODUCTION

Numerous studies have reported on the short- and intermediate-term successful results of anterior cruciate ligament (ACL) reconstruction.^{3, 10, 32, 54, 56} However, while researchers have documented the long-term risks of osteoarthritis following ACL reconstruction^{1, 2, 4, 6, 11, 13, 19, 20, 25, 27–29, 31, 33, 40–42, 45, 52, 55, 57} and incidence of subsequent surgeries and ACL graft tears,^{7, 10} there has been less discussion of patient-specific risk factors and patient-reported outcome measures following ACL reconstruction.³⁶ Patient-reported outcome measures offer a complementary set of diagnostic tools with which to quantify “outcome”. A subset of these patient-reported outcome measures have been validated, defined as undergone testing for the instrument’s reliability, responsiveness, and validity (i.e. content validity, face validity, construct validity and/or criterion validity). During the last decade, validated patient-reported outcome measures have become more popular, as these measures have provided invaluable information to researchers about the relative success of orthopaedic interventions.^{5, 30, 46, 49} These instruments document information about knee function, symptoms, and quality of life from the patient’s point of view, and have been reported to be strong proxies for onsite assessments.⁵⁸ Because patient-

reported outcomes have come to play an increasingly large role in the assessment of outcomes after treatment, they have become a recommended component of all clinical trials.⁹ Additionally, a unique advantage of questionnaire-based validated patient-reported outcomes is the ability to follow hundreds or thousands of patients at a fraction of the cost, and with improved follow-up compared to the logistic difficulties of having patients return for onsite evaluations (e.g., clinical exam, radiographs, etc).

Ten-year patient-reported outcomes (e.g., the International Knee Documentation Committee [IKDC]⁵⁰ form, the Knee injury and Osteoarthritis Outcome Score [KOOS],⁴⁹ and the Marx activity rating scale³⁸) as well as the modifiable risk factors for an individual patient's worse outcomes have not yet been determined in a large prospective cohort with high (>80%) follow-up. In a systematic review³⁶ on 10-year patient-reported outcomes, only three studies reported use of the IKDC: Lebel²⁷ (n=154; 67% follow-up), Bourke⁸ (n=755; 79% follow-up), and Shelbourne⁵² (n=1276; 72% follow-up), with both larger studies excluding long-term graft failure or contralateral ACL tears. The KOOS has been reported in two studies, by Barenius⁴ and Moller³⁹, with a total sample size of 226 and with both greater than 80% follow-up. The Marx activity scale has not been reported at 10 years.³⁶ In a 2014 systematic review on the long-term natural history of ACL injuries, Chalmers et al.¹⁰ identified 27 studies that reported outcomes following surgical reconstruction (incidence of subsequent surgeries and Tegner activity level). Unfortunately, the mean sample size of the 27 operative cohorts was n=59 (range, 22 to 181), with a cumulative sample size of 1585 patients. As such, the ability to control for confounding factors which may influence outcomes has been extremely limited.

The Multicenter Orthopaedics Outcome Network (MOON) population cohort was designed in 2002 to prospectively determine which variables at the time of an ACL injury (including previous surgical history of the knee, patient demographics, mechanism of the current injury, surgical technique/choices at the time of the index ACL surgery, concomitant meniscal and/or articular cartilage pathology and treatment, among other potential modifiable and non-modifiable variables), would influence and predict both short and long-term outcomes following ACL reconstruction. This consortium has a proven ability to maintain 80% follow-up at 2 and 6 years as well as capture important time-dependent risk factors like activity level and additional surgery.^{12, 15, 18, 53} Utilizing this infrastructure, the objective of the current study was to identify both patient-specific risk factors as well as the sports-specific patient-reported outcomes measures (IKDC, KOOS, and Marx activity scale) 10 years after ACL reconstruction in a prospective longitudinal cohort. We hypothesized that meniscus and articular cartilage injuries (noted at the time of the index ACL reconstruction), revision ACL reconstruction, any subsequent knee surgeries occurring after the index ACL reconstruction, and certain demographic characteristics would be significant risk factors for inferior 10-year patient-reported outcomes.

METHODS

Setting and Study Population

After obtaining approval from each site's respective institutional review boards, the multicenter consortium began enrolling patients in 2002. This consortium consisted of 7

sites (Vanderbilt University, Nashville, TN; Cleveland Clinic Foundation, Cleveland, OH; The Ohio State University, Columbus, OH; University of Iowa, Iowa City, IA; Washington University in St. Louis, MO; Hospital for Special Surgery, New York, NY; and University of Colorado, Boulder, CO) with 12 surgeons over a 3 year enrollment period (2002–2004). One university functioned as the data processing center for the study and was responsible for entering baseline data and collecting follow-up data on all patients. The trial is registered at ClinicalTrials.gov: NCT00463099. The details of enrollment, patient-reported outcome capture, surgical documentation at ACL reconstruction and method of follow-up has been described previously.¹²

All patients who underwent unilateral primary or revision ACL reconstruction surgery between January 1, 2002 and December 31, 2004, were eligible for enrollment. During this time frame, sites identified 1678 subjects who were slated to have an ACL reconstruction. A total of 1592 subjects met the study's inclusion criteria and were enrolled into the study (Figure 1).

Data Sources and Measurement

After informed consent was obtained, each participant was asked to complete a 13-page questionnaire encompassing baseline demographics, injury descriptors, sports participation level, comorbidities, knee surgical history, and patient-reported outcome measures that included the IKDC,^{22, 23} the five KOOS subscales (symptoms, pain, activities of daily living [ADL], sports and recreation, knee-related quality of life [QOL])⁴⁹ and the Marx activity rating scale.³⁸ The questions related to the IKDC and KOOS pertain to the time frame of the patient's pain and function level within the past week, while the Marx activity rating scale queries the patient's activity level from the past year. As such, the baseline IKDC and KOOS scores represent the ACL-deficient post-injury/pre-surgery state, while the baseline Marx activity score likely reflects the patient's pre-injury state. The validity, reliability, responsiveness to clinical change, and minimal clinically meaningful differences of these instruments have been previously documented (IKDC^{22–24}; KOOS^{44, 48, 49}; Marx³⁸). Each surgeon completed a detailed form that documented the results of the examination under anesthesia, surgical technique, and arthroscopic findings and treatment of concomitant meniscus and cartilage injury. Surgeon documentation of articular cartilage injury was recorded, based on the modified Outerbridge classification.^{14, 37, 43} Presence of linear cracks/fracture lines in the articular cartilage surfaces were also noted (if applicable). Meniscus injuries were classified by size, location, and partial versus complete tears, while treatment was recorded as not treated, repair, or extent of resection.¹⁶ After surgery, the patients were given a uniform set of standardized, evidence-based rehabilitation guidelines.^{59–61} Completed data forms were mailed from each participating site to the data coordinating center. Data from both the patient and surgeon questionnaires were scanned with Teleform software (Cardiff Software Inc., Vista, California, USA) using optical character recognition, and the scanned data were verified and exported to a master database. A series of logical error and quality control checks were subsequently performed. Cases which failed these checks were tagged and verified against the source documents in order to resolve prior to data analysis.

Follow-up

Two, six, and ten-year follow-up were completed by mail with re-administration of the same questionnaire that the patients completed at baseline (defined as the time of index ACL surgery). In addition, patients were also contacted to determine whether any underwent additional surgical knee procedures since baseline (e.g., revision ACL reconstruction on the ipsilateral knee, primary ACL reconstruction on the contralateral knee, and/or any arthroscopic procedures on either knee). Every effort was made to obtain the operative note on these additional surgical procedures. Follow-up was managed at a central coordinating site, but also required surgeon investigators and/or their respective sites to aid in contacting patients, in order to achieve a high level of follow-up.

Statistical Analyses

To determine the association between independent (risk factor) variables and 10-year patient-reported outcome measures, multivariable regression models were utilized. Multivariable analysis was used to determine which baseline variables measured at the time of index ACL surgery were significant predictors (risk factors) of the IKDC, KOOS, and Marx scores at 2, 6, and 10 years after surgery. Longitudinal analysis was performed using proportional odds ordinal logistic regression in lieu of linear regression models because the assumption of normal linear residuals was violated.⁵¹

The dependent variables (IKDC, KOOS, and Marx) were treated as continuous and consisted of the 10-year IKDC (scored 0 [worst] to 100 [best]), the five KOOS subscales (scored 0 [worst] to 100 [best]), and the Marx (scored 0 [low activity] to 16 [highest activity]). Independent patient covariates (risk factors) in the model included age at the time of surgery, gender, ethnicity, education level, body mass index (BMI), smoking status, sport played at the time of injury, competition level, baseline activity level as assessed using the Marx activity rating scale, and the baseline outcome measure (IKDC, KOOS, or Marx).

Independent surgical risk factors included surgeon, history of previous meniscal surgery (medial and/or lateral) at the time of index ACL reconstruction (yes/no), history of previous ACL reconstruction on the contralateral knee (yes/no), primary vs. revision surgery, graft type (autograft patellar bone-tendon-bone (BTB), autograft soft tissue, allograft BTB, allograft soft tissue), and concomitant MCL or LCL pathology. Meniscal injuries noted at the time of the index ACL reconstruction were classified by location (medial, lateral), size, and treatment (categorized as not treated, repaired, or percent excised). Excision options were categorized as none, 33%, 67%, or 100% excision for each segment (anterior and/or posterior). For this study, we used the largest excision in either segment. Articular cartilage variables noted at the time of the index ACL reconstruction were grouped by location to include the medial compartment (medial femoral condyle, medial tibial plateau), lateral compartment (lateral femoral condyle, lateral tibial plateau), and patellofemoral (patella, trochlea). Severity of articular cartilage degeneration in each location was categorized according to the modified Outerbridge classification¹⁴ and included normal, grade 1 (softening), grade 2 (fraying or fissures), grade 3 (partial thickness loss with fibrillation), or grade 4 (full thickness loss with exposed subchondral bone). If pathology was present in both locations within a compartment (e.g., lateral femoral condyle and lateral tibial plateau

for the lateral compartment), the highest grade from either location was selected and extracted for analyses. Presence of linear cracks (fracture lines) in the articular cartilage surfaces were also noted (yes/no), and grouped in the same way as the articular cartilage degeneration pathology: medial compartment, lateral compartment, and patellofemoral compartment. Articular cartilage fracture pathology was defined as a ‘yes’ if any surface within a compartment presented with these linear cracks/fracture lines at the time of the index ACL reconstruction.

An additional independent surgical risk factor included in the model was preoperative laxity of the knee (defined as “high grade” laxity = yes or no). “High grade” laxity was determined by having either a Lachman or anterior drawer examination greater than a 10mm difference from the contralateral side or a 3+ pivot-shift during their examination under anesthesia. Previous literature has shown this definition to be predictive of increased odds of having a subsequent revision ACL surgery.^{34, 35}

Description of the cohort was performed using counts and percentages for describing categorical data and medians and inner quartile range (IQR) for describing continuous data. Each of the seven outcomes was recorded at 10 years and risk factors were recorded at the time of surgery. The risk factors, baseline outcomes scores, BMI, smoking status and occurrence of subsequent surgery to the ipsilateral knee and contralateral knee were recorded at 2 years post-surgery and 6 years post-surgery. Therefore, a model at baseline, 2 years after surgery and 6 years after surgery was created to predict 10-year outcome scores with updated risk factors. Since the amount of missing information was small, only complete cases were used in the modeling and no imputation was used. All models were constructed using a proportional odds regression model, because this method has been reported to produce better predictive models.⁵¹ The baseline model was created using all risk factors available at baseline and reduced using a step-down reduction process, where the removal of each variable was evaluated by determining which had the smallest effect on the R^2 and was stopped when the adjusted R^2 was maximized and the Bayesian Information Criterion (BIC) was minimized. The models at 2 years and 6 years were created using the same variables in the baseline model, while updating BMI, smoking status and baseline outcome scores if they were included within the baseline model, and added subsequent surgeries. The performance of each model was measured using bootstrap optimize correction to the adjusted R^2 . Each model was then programmed into an online calculator for an easier assessment of a patient’s risk at time of surgery, 2 years or 6 years after surgery.

Regarding clinically meaningful change in score, we utilized 11 points for the IKDC,²¹ 8 points for the KOOS,⁴⁷ and 2 points for the Marx activity scale. All statistical analysis was performed using R open-source statistical software (2016, Vienna, Austria. URL <https://www.R-project.org/>).

RESULTS

Study Population

A total of 1592 patients fit the inclusion criteria and were enrolled. Ten-year follow-up was obtained on 83% (1320) [86% (1379) at 2 years, 86% (1375) at 6 years], while subsequent

surgery information (performed after the index ACL surgery, if applicable) was obtained on over 90% of the cohort.

Baseline demographic and clinical characteristics of the analyzed cohort are provided in Table 1. The study population was 57% male with a median age of 24 years (IQR: 17, 35) at the time of their ACL reconstruction. Ninety percent (90%) underwent a primary ACL reconstruction, while the remaining 10% underwent a revision ACL reconstruction. Graft choice at the time of surgery was 42% autograft BTB, 31% autograft soft tissue, and 27% allograft. Thirty-seven percent (37%) had documented medial meniscal pathology at the time of their surgery, while 45% had documented lateral meniscal pathology. Articular cartilage pathology (grades 2–4) at the time of ACL surgery was less prevalent in this cohort: 24% in the medial compartment, 22% in the lateral compartment, and 22% in the patellofemoral compartment. Interestingly, 37% of patients in this cohort were classified as having “high grade” knee laxity preoperatively.

10-Year Population Outcomes

Both IKDC and KOOS scores for the entire cohort population significantly improved after 2 years and were maintained at 6 and 10 years (Table 2; Figure 2a,b). Interestingly, Marx activity level for the cohort population scores dropped markedly over time (Figure 2c), from a median score of 12 points at baseline, 9 points at 2 years, 7 points at 6 years, to 6 points at 10 years (Table 2).

Patient-Specific Risk Factors

The patient-specific risk factors for inferior 10-year outcomes are reported in Table 3 and summarized in Table 4. The consistent risk factors for inferior 10-year outcomes across all outcome scales were lower baseline outcome scores, higher BMI, and having a medial meniscus procedure done prior to the index ACL reconstruction (Tables 3, 4). Other significant risk factors shown in the majority of our outcome scales (but not all), were female gender, higher age, smoker at baseline, lower baseline activity level, lower educational level, having a revision ACL reconstruction, having grades 3–4 articular cartilage pathology in the medial, lateral or patellofemoral compartments at the time of index ACL surgery, and having any subsequent ipsilateral surgery after the index ACL surgery (Tables 3, 4). Having either a lateral meniscus procedure done prior to the index ACL reconstruction or having a lateral meniscectomy at the time of the index ACL reconstruction were significant risk factors for poorer 10-year KOOS QOL outcomes, while having high-grade preoperative knee laxity was a significant independent risk factor for worse 10-year Marx activity levels.

Sport or level of competition, graft type (autograft BTB, autograft soft tissue, allograft), MCL or LCL pathology, medial meniscus pathology at the time of ACL reconstruction, and surgeon were not found to be significant risk factors.

Relative Strength of Association between Predictor Variables and Outcomes

The relative strength of associations between predictor variables and IKDC, KOOS, and Marx activity levels at 10 years are shown in Figures 3a–g. These figures show the

independent variables on the vertical axis, and the relative portion of the variation in the outcome accounted for by the given variable on the horizontal axis. This importance is measured by Wald chi-square statistics minus the degrees of freedom. The overarching result, regardless of outcome instrument, is that the score recorded at baseline has a dominating influence on the outcome score at 10 years post-surgery.

DISCUSSION

The major findings of this study are that both short- and long-term IKDC and KOOS outcomes significantly improve after an ACL reconstruction, and that these outcome levels are maintained through 10 years. However, Marx activity levels steadily decline over time. There are also patient-specific risk factors that significantly influence 10-year patient-reported outcomes. The risk factors which were found to negatively impact 10-year IKDC, KOOS, and Marx activity level outcomes included lower baseline outcome scores, higher BMI, being a smoker at baseline, history of a medial or lateral meniscus procedure done prior to the index ACL reconstruction, having a revision ACL reconstruction, lateral meniscectomy performed at the time of the index ACL reconstruction, grades 3–4 articular cartilage pathology in the medial, lateral or patellofemoral compartments at the time of the index ACL reconstruction, and having any subsequent ipsilateral surgery after the time of the index ACL reconstruction. Unfortunately, we still had insufficient sample size to model the interaction of meniscus injury and treatment with articular cartilage damage in the same compartment.

An unanticipated positive result was that the 10-year population IKDC and KOOS scores were similar to the 2- and 6-year levels (Figure 2a, b). However, patient activity level steadily declined over time. This finding, along with previous work from others,^{17, 26, 38} highlights the complexity of activity level. As we age, we may tend to be less active. However, unacceptable symptoms may accelerate this relative inactivity, and some treatments may improve symptoms so much that they allow for a higher activity.

The 10-year IKDC and KOOS QOL subscale identified nearly the same risk factors for worse outcome except for three variables: the IKDC uniquely identified lower education and the KOOS QOL uniquely identified higher age and previous lateral meniscectomy as risk factors for worse outcome. In our previous work at 2 and 6 years, the KOOS QOL scores tracked most closely with the IKDC.¹² Thus, risk factors consistent across two “independent” scales are more likely to be more clinically meaningful. These risk factors should be explored to improve ACL reconstruction outcomes. Potential modifications to risk factors are to lower BMI, encourage smoking cessation, prevent/minimize subsequent ACL failure (revision ACL reconstructions), and identify optimal interventions for grades 3–4 articular cartilage pathology. A consistent observation was that a grade 3 or 4 articular cartilage lesion in the medial, lateral, or patellofemoral compartments at the time of the index ACL reconstruction predicted worse 10-year IKDC and KOOS outcome scores. The majority of these lesions were treated with chondroplasty/debridement, which negated our ability to model treatment options, including no treatment, debridement, and all various cartilage restorative procedures. Regardless, these patients should be counseled about a

worse long-term prognosis. In the future, additional sample size may allow us to model a more diverse set of articular cartilage treatment options.

Surprisingly, meniscus pathology and treatment done at the time of the index ACL procedure were not risk factors for 10-year outcomes as they were at 6 years.¹² The exception to this were patients who had a lateral meniscectomy at the time of the index ACL procedure were found to have significantly lower KOOS quality of life scores at 10 years. Meniscal repairs done at the time of the index ACL procedure did not affect 10 year outcomes. However, having a medial meniscus procedure prior to the index ACL reconstruction was an independent predictor of having significantly poorer IKDC, KOOS, and Marx activity level scores at 10 years.

The risk factors identified for poor 10-year activity levels included lower baseline activity level, higher age, female gender, higher BMI, lower education level, having a medial meniscus procedure done prior to the index ACL reconstruction, and having high-grade pre-operative knee laxity. These factors are similar to previously reported risk factors at 6-year follow-up.¹²

To assess an individual's expected outcome, the entire spectrum of potential risk factors must be simultaneously evaluated either in a nomogram or risk calculator. An online risk calculator is available at Cleveland Clinic Quantitative Health Services (<http://rcalc.ccf.org>) for physicians and patients to evaluate their expected 10-year outcomes with baseline, 2-year, and 6-year data. The R² value provides a measure of the variability in the 10-year IKDC, KOOS and Marx models, and was found to consistently improve from baseline to 2 years to 6 years. Thus, updating the baseline factors with current IKDC, KOOS and Marx scores, along with a patient's current BMI, smoking status, and subsequent surgery information on either knee would provide more accurate estimates.

The main limitations of this study are that we did not obtain onsite measures (such as clinical exams, imaging, or other instrumented-based measures), and our sample size was too small to model the interaction between meniscus and articular cartilage pathology within the same compartment. The effect of treatment on grade 3 or 4 articular cartilage lesions could also not be assessed, given that the majority of these lesions were treated via chondroplasty. The lack of structural imaging (radiological or magnetic resonance imaging evaluation) to confirm the status of the articular cartilage and meniscus at 10+ years post-surgery is an area of future interest. An additional study limitation is the acknowledgement that baseline Marx activity scores likely reflect a patient's pre-injury state, whereas the baseline KOOS and IKDC scores represent the ACL-deficient post-injury/pre-surgery state. Regarding activity levels over time, it remains unclear whether patients modified their activity level to one that allowed for acceptable symptoms or not.

CONCLUSIONS

Patients are able to perform sports-related functions and maintain a relatively high knee-related quality of life 10 years after ACL reconstruction, although activity level markedly declines over time. Multivariable analysis identified several key modifiable risk factors that

significantly influence outcome. This information can be helpful to physicians counseling patients' expectations of outcome after ACL reconstruction. Finally, intervention strategies for the potentially modifiable risk factors reported in this study should be developed and studied to assess their potential to improve outcomes following ACL reconstruction.

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What is known about the subject

Several demographic risk factors and their treatment along with subsequent surgery have been identified in cohorts at intermediate follow-up (5–6 years) after ACL reconstruction.

What this study adds to existing knowledge

No comprehensive multivariable analysis of an ACL reconstruction prospective longitudinal cohort 10 years after surgery has been performed.

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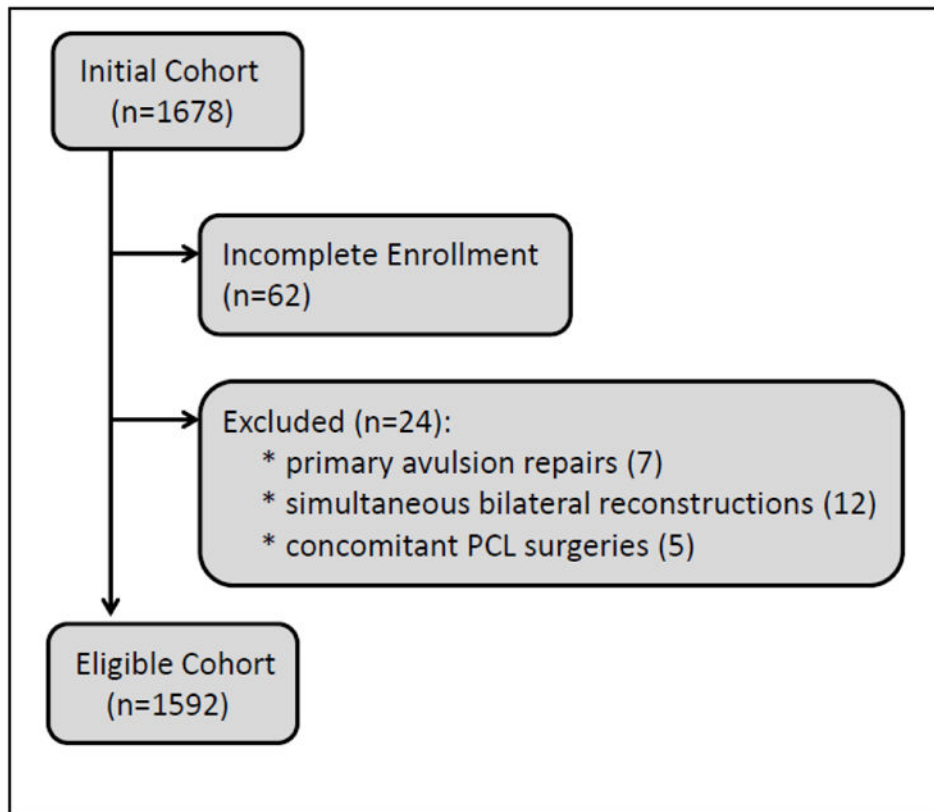
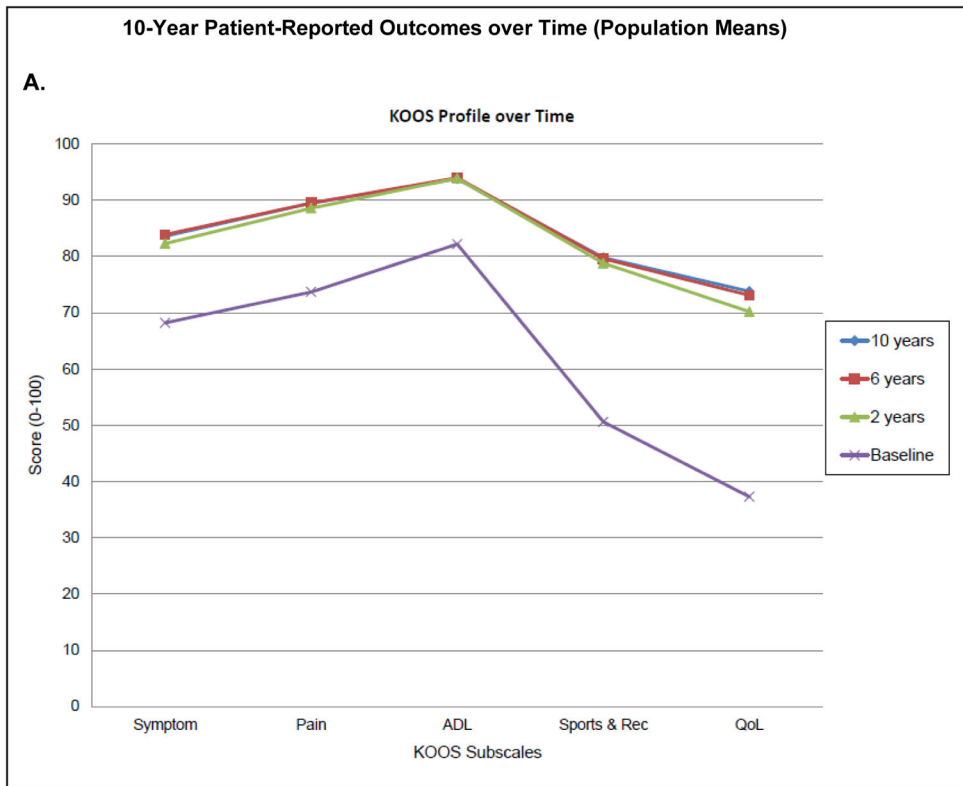


Figure 1.
Enrollment Flow Diagram



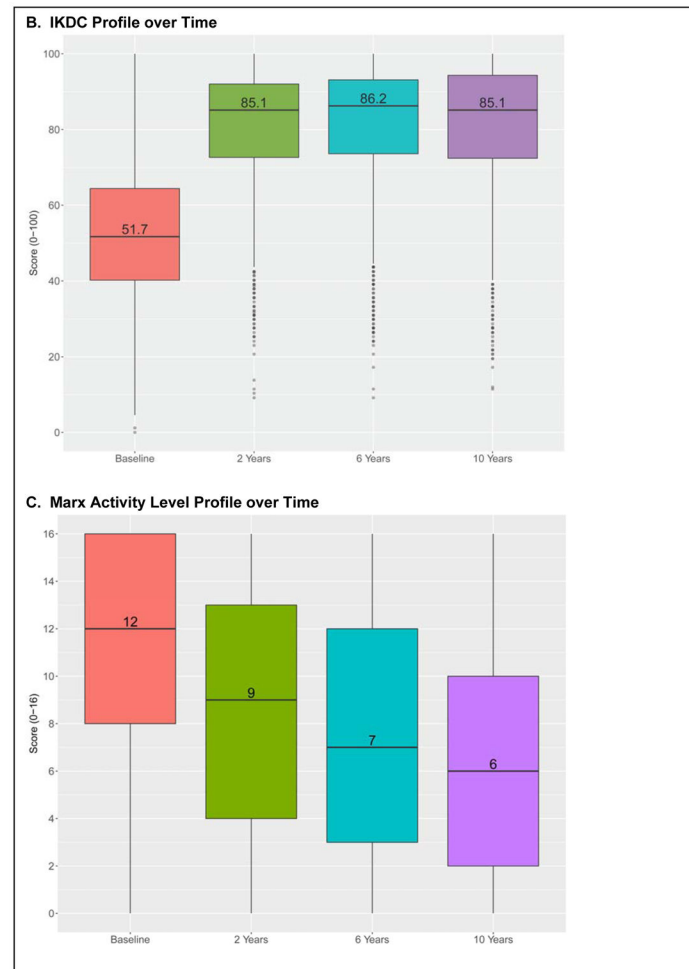


Figure 2. 10-Year Patient-Reported Outcomes over Time (Population Means). Figure 2a: KOOS profile over time; Figure 2b: IKDC profile over time; Figure 2c: Marx activity level profile over time.

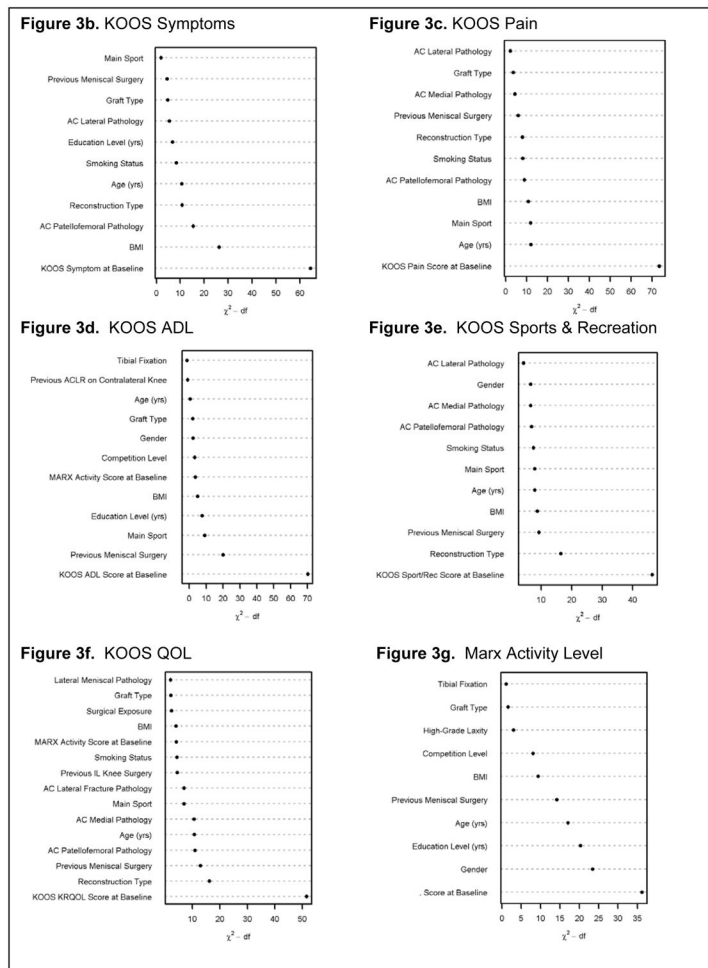
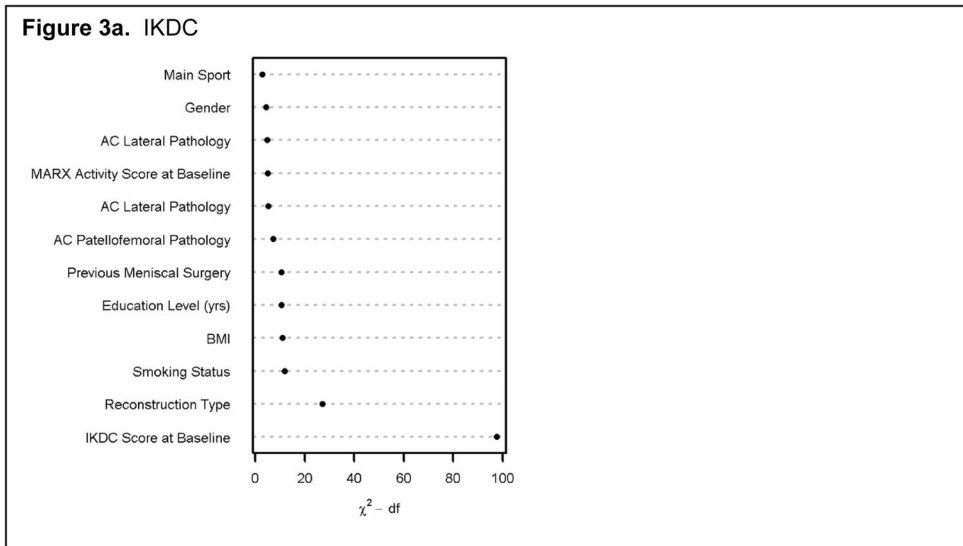


Figure 3.

The relative strength of association between predictor variables and IKDC (3a), KOOS (symptoms subscale – 3b; pain subscale – 3c; activities of daily living (ADL) – 3d; sports and recreation subscale – 3e; quality of life (QOL) – 3f), and Marx activity levels (3g) at 10 years.

Key: reconstruction type = primary versus revision ACL reconstruction; AC = articular cartilage; BMI = body mass index; IL = ipsilateral.

Table 1

Baseline and Intermediate Patient and Surgical Characteristics of the Study Cohort

Patient Demographic Factors	
Age	24 (17, 35)
Gender	
• Male	902 (57%)
• Female	690 (43%)
Ethnicity/Race	
• White	1,333 (84%)
• Black	135 (8%)
• Other	114 (7%)
• Missing	10 (1%)
Baseline BMI	25 (22.4, 28.1)
• Missing	35 (2%)
Baseline Smoking Status	
• Never	1,248 (78%)
• Quit	158 (10%)
• Current	170 (11%)
• Missing	16 (1%)
Education level (years)	14 (11, 16)
• Missing	11 (1%)
Main Sport	
• None	123 (8%)
• Baseball / Softball	141 (9%)
• Basketball	358 (23%)
• Football	174 (11%)
• Soccer	212 (13%)
• Other	577 (36%)
• Missing	7 (0%)
Competition Level	
• None	205 (13%)
• Recreational	527 (33%)
• Amateur	222 (14%)
• High School	440 (28%)
• College	159 (10%)
• Semi-Pro / Professional	30 (2%)
• Missing	9 (0%)

Surgical Characteristics	
Surgeon Volume	
• #1	75 (5%)
• #2	14 (1%)
• #3	459 (29%)
• #4	86 (5%)
• #5	27 (2%)
• #6	95 (6%)
• #7	301 (19%)
• #8	7 (0%)
• #9	72 (5%)
• #10	304 (19%)
• #11	147 (9%)
• #12	5 (0%)
Reconstruction type	
• Primary	1,439 (90%)
• Revision	153 (10%)
Graft type	
• Autograft (BTB)	674 (42%)
• Autograft (Soft Tissue)	496 (31%)
• Allograft (BTB)	122 (8%)
• Allograft (Soft Tissue)	300 (19%)
Previous ACL reconstruction on contralateral knee	
• Yes	138 (9%)
• No	1,454 (91%)
Previous medial meniscal surgery	
• Yes	151 (9%)
• No	1,441 (91%)
Previous lateral meniscus surgery	
• Yes	67 (4%)
• No	1,525 (96%)
MCL Pathology	
• Normal/Grade 1	1,497 (94%)
• Grades 2/3	95 (6%)
LCL Pathology	
• Normal/Grade 1	1,554 (98%)
• Grades 2/3	38 (2%)
Medial Meniscal pathology	
• No Tear	999 (63%)
• No Treatment for Tear	87 (5%)

Surgical Characteristics	
• Repair	199 (12%)
• Excision - 1/3	72 (5%)
• Excision - 2/3	193 (12%)
• Excision – all	32 (2%)
• Other	10 (1%)
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Lateral Meniscal pathology	
• No Tear	880 (55%)
• No Treatment for Tear	167 (10%)
• Repair	99 (6%)
• Excision - 1/3	260 (16%)
• Excision - 2/3	155 (10%)
• Excision – all	24 (2%)
• Other	7 (0%)
<hr/>	
AC pathology (medial compartment)	
• Normal/Grade 1	1,207 (76%)
• Grade 2	229 (14%)
• Grades 3–4	156 (10%)
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AC pathology (lateral compartment)	
• Normal/Grade 1	1,252 (79%)
• Grade 2	231 (15%)
• Grades 3–4	109 (7%)
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AC pathology (patellofemoral)	
• Normal/Grade 1	1,241 (78%)
• Grade 2	202 (13%)
• Grades 3–4	149 (9%)
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AC pathology – linear cracks/fracture lines (medial compartment)	
• Yes	119 (7%)
• No	1,473 (93%)
<hr/>	
AC pathology – linear cracks/fracture lines (lateral compartment)	
• Yes	176 (11%)
• No	1,416 (89%)
<hr/>	
AC pathology – linear cracks/fracture lines (patellofemoral compartment)	
• Yes	31 (2%)
• No	1,561 (98%)
<hr/>	
Surgical exposure	
• 1 incision	1,103 (69%)
• 2 incision	488 (31%)
• Missing	1 (0%)
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Notchplasty	

Surgical Characteristics	
• Yes	1,545 (97%)
• No	47 (3%)
High-grade Laxity	
• Yes	587 (37%)
• No	1,005 (63%)

Intermediate Variables	
2-year BMI	25.1 (22.6, 28.1)
• Missing	237 (15%)
6-year BMI	25.8 (23.0, 28.7)
• Missing	224 (14%)
2-year Smoking Status	
• Current	127 (8%)
• Quit	201 (13%)
• Never	1,013 (64%)
• Missing	251 (16%)
6-year Smoking Status	
• Current	156 (10%)
• Quit	238 (15%)
• Never	965 (61%)
• Missing	233 (15%)
Subsequent surgery (ipsilateral knee)	
• None	1,223 (77%)
• Scope	221 (14%)
• Revision ACL reconstruction	132 (8%)
• Total knee arthroplasty	16 (1%)
Subsequent surgery (contralateral knee)	
• None	1,310 (82%)
• Scope	78 (5%)
• ACL reconstruction	140 (9%)
• Total knee arthroplasty	3 (0%)
• Missing	61 (4%)

Key: Continuous variables are listed as median (25%, 75% quartiles). Categorical variables are listed as frequency counts, n, (percentage). BMI = body mass index; BTB = bone-patellar tendon-bone; AC = articular cartilage.

Table 2

Median (IQR) of KOOS, IKDC, and Marx Outcomes over Time

	Score Range	Baseline	2 Years	6 Years	10 Years
KOOS symptoms	0-100	71 (57, 82)	86 (75, 93)	89 (75, 96)	89 (75, 96)
KOOS pain	0-100	75 (61, 89)	92 (83, 97)	94 (86, 100)	94 (86, 100)
KOOS ADL	0-100	88 (72, 96)	99 (93, 100)	99 (93, 100)	99 (93, 100)
KOOS sports & recreation	0-100	50 (25, 75)	85 (70, 95)	85 (70, 100)	90 (70, 100)
KOOS QOL	0-100	38 (25, 50)	75 (56, 88)	75 (63, 94)	75 (63, 94)
IKDC	0-100	52 (40, 64)	85 (72, 92)	86 (74, 93)	85 (72, 94)
Marx Activity Level	0-16	12 (8, 16)	9 (4, 13)	7 (3, 12)	6 (2, 10)

Key: ADL = activities of daily living; QOL = quality of life

Table 3

Significant Odds Ratios (95% CI) for Variables in Model

	Comparison	Worse Outcome	IKDC	KOOS				Sports/Rec	QOL	Marx
				Symptoms	Pain	ADL				
Baseline Outcome Score		lower baseline score	1.03 (1.03, 1.04) p<0.0001	1.02 (1.02, 1.03) p<0.0001	1.03 (1.02, 1.04) p<0.0001	1.03 (1.01, 1.02) p<0.0001	1.01 (1.01, 1.02) p<0.0001	1.02 (1.01, 1.03) p<0.0001	1.08 (1.06, 1.11) p<0.0001	
Patient Demographics										
Age		older age		1.02 (1.01, 1.04) p=0.0007	1.02 (1.01, 1.04) p=0.0003		1.02 (1.01, 1.03) p=0.0003	1.02 (1.01, 1.04) p=0.0007	0.97 (0.96, 0.98) p<0.0001	
Gender	male vs. female	females	1.30 (1.04, 1.62) p=0.021				1.37 (1.09, 1.71) p=0.006		1.70 (1.38, 2.10) p<0.0001	
BMI		higher BMI	0.96 (0.93, 0.98) p=0.0005	0.94 (0.92, 0.96) p<0.0001	0.96 (0.93, 0.98) p=0.0006	0.97 (0.94, 0.99) p=0.016	0.96 (0.94, 0.99) p=0.002	0.97 (0.95, 1.00) p=0.025	0.96 (0.94, 0.98) p=0.001	
Smoking status	never vs. quit	quit smoking	0.59 (0.42, 0.83) p=0.002	0.64 (0.46, 0.89) p=0.008	0.68 (0.49, 0.95) p=0.025		0.68 (0.48, 0.97) p=0.031			
	never vs. current	current smoker	0.62 (0.43, 0.90) p=0.011	0.66 (0.45, 0.95) p=0.026	0.60 (0.41, 0.88) p=0.009		0.62 (0.42, 0.90) p=0.013			
Education level		lower education	1.06 (1.03, 1.10) p=0.0006	1.06 (1.02, 1.10) p=0.006		1.07 (1.02, 1.12) p=0.004			1.10 (1.06, 1.15) p<0.0001	
Baseline Marx Activity level		lower activity level	1.03 (1.01, 1.06) p=0.013			1.03 (1.00, 1.06) p=0.031		1.03 (1.00, 1.05) p=0.024	1.08 (1.06, 1.11) p<0.0001	
Main sport	none vs. football	football				0.47 (0.23, 0.96) p=0.038				
	none vs. other	none					1.64 (1.06, 2.53) p=0.027			

	Comparison	Worse Outcome	IKDC	Symptoms	Pain	KOOS		Sports/Rec	QOL	Marx
						ADL	ADL			
Competition level	None vs. high school	none					1.75 (1.01, 3.03) p=0.048			
	None vs. recreational	none					1.70 (1.05, 2.76) p=0.03			
	no vs. yes	yes								1.08 (1.06, 1.11) p<0.0001
Surgical Factors										
Reconstruction type	primary vs. revision	revision	0.37 (0.26, 0.54) p<0.0001	0.51 (0.35, 0.75) p=0.0006	0.57 (0.39, 0.82) p=0.003			0.46 (0.32, 0.66) p<0.0001	0.44 (0.30, 0.65) p<0.0001	
	Medial meniscus procedure prior to index ACL reconstruction	yes	0.52 (0.36, 0.76) p=0.0006	0.64 (0.44, 0.93) p=0.019	0.60 (0.42, 0.88) p=0.008	0.43 (0.31, 0.62) p<0.0001		0.53 (0.36, 0.78) p=0.001	0.49 (0.33, 0.71) p=0.0002	0.48 (0.33, 0.69) p<0.0001
Lateral meniscus procedure prior to index ACL reconstruction	no vs. yes	yes							0.54 (0.32, 0.90) p=0.019	
Lateral meniscus pathology	no tear vs. excision	excision							0.80 (0.64, 1.00) p=0.05	
AC Medial pathology	normal vs. Grades 3–4	Grades 3–4	0.70 (0.49, 0.99) p=0.047					0.65 (0.45, 0.94) p=0.022	0.68 (0.48, 0.98) p=0.036	
AC Lateral pathology	normal vs. Grades 3–4	Grades 3–4	0.58 (0.39, 0.86) p=0.008	0.57 (0.38, 0.86) p=0.006	0.66 (0.44, 0.99) p=0.043			0.60 (0.40, 0.90) p=0.013		
AC Lateral pathology	normal vs. fracture lines	linear crack/fracture lines							0.61 (0.43, 0.86) p=0.005	

	Comparison	Worse Outcome	IKDC	KOOS				QOL	Marx
				Symptoms	Pain	ADL	Sports/Rec		
AC Patellofemoral pathology	normal vs. Grades 3-4	Grades 3-4	0.58 (0.41, 0.83) p=0.003	0.46 (0.32, 0.66) p<0.0001	0.53 (0.37, 0.77) p=0.0009	0.58 (0.39, 0.84) p=0.0005	0.51 (0.35, 0.74) p=0.0004		
Intermediate Variables									
2-year Outcome score		lower 2 year score	1.06 (1.06, 1.07) p<0.0001	1.06 (1.06, 1.07) p<0.0001	1.03 (1.02, 1.03) p<0.0001	1.01 (1.01, 1.02) p<0.0001	1.05 (1.04, 1.05) p<0.0001	1.15 (1.12, 1.18) p<0.0001	
2-year Marx activity level		lower activity level	1.03 (1.01, 1.05) p=0.015			1.03 (1.01, 1.06) p=0.011	1.03 (1.01, 1.05) p=0.015	1.15 (1.12, 1.18) p<0.0001	
2-year BMI		higher BMI	0.97 (0.95, 1.00) p=0.0005	0.94 (0.92, 0.96) p<0.0001	0.96 (0.94, 0.99) p=0.0004	0.97 (0.94, 1.00) p=0.037	0.97 (0.94, 0.99) p=0.011	0.96 (0.93, 0.99) p=0.002	
2-year Smoking status	never vs. quit	quit smoking	0.70 (0.52, 0.94) p=0.017	0.71 (0.53, 0.94) p=0.019					
	never vs. current	current smoker			0.59 (0.39, 0.89) p=0.011		0.62 (0.41, 0.92) p=0.018		
2-year Subsequent Surgery (ipsilateral knee)	none vs. scope	scope	0.52 (0.38, 0.71) p<0.0001	0.50 (0.36, 0.69) p<0.0001	0.41 (0.30, 0.55) p<0.0001	0.54 (0.40, 0.74) p=0.0001	2.24 (1.47, 3.41) p=0.0002		
	none vs. revision ACL reconstruction	Revision ACL reconstruction	0.48 (0.33, 0.71) p=0.0002	0.48 (0.32, 0.70) p=0.0002	0.39 (0.27, 0.58) p<0.0001	0.51 (0.34, 0.77) p=0.0013	0.34 (0.23, 0.50) p<0.0001		
2-year Subsequent Surgery (contralateral knee)	none vs. scope	scope					1.48 (1.04, 2.12) p=0.031		
	none vs. ACL reconstruction	ACL reconstruction							
6-year Outcome score		lower 6 year score	1.10 (1.09, 1.11) p<0.0001	1.10 (1.09, 1.10) p<0.0001	1.03 (1.02, 1.03) p<0.0001	1.12 (1.11, 1.14) p<0.0001	1.01 (1.01, 1.02) p<0.0001	1.24 (1.21, 1.27) p<0.0001	

	Comparison	Worse Outcome	IKDC	KOOS			QOL	Marx
				Symptoms	Pain	ADL		
6-year Marx activity level		lower activity level	1.04 (1.02, 1.06) p=0.0004		1.04 (1.02, 1.07) p=0.002			1.24 (1.21, 1.27) p<0.0001
6-year BMI		higher BMI		0.95 (0.93, 0.97) p<0.0001	0.96 (0.94, 0.99) p=0.002		0.96 (0.94, 0.99) p=0.003	0.95 (0.93, 1.00) p=0.036
6-year Smoking status	never vs. quit	quit smoking	0.74 (0.57, 0.98) p=0.034					
	never vs. current	current smoker			0.65 (0.45, 0.93) p=0.017		0.61 (0.42, 0.87) p=0.006	
6-year Subsequent Surgery (ipsilateral knee)	none vs. scope	scope	0.57 (0.42, 0.76) p=0.0001	0.55 (0.41, 0.74) p<0.0001	0.41 (0.31, 0.55) p<0.0001	0.58 (0.42, 0.78) p=0.0004	0.42 (0.31, 0.56) p<0.0001	1.71 (1.15, 2.55) p=0.008
	none vs. revision ACL reconstruction	Revision ACL reconstruction	0.58 (0.40, 0.86) p=0.006	0.55 (0.38, 0.81) p=0.002	0.38 (0.26, 0.55) p<0.0001	0.61 (0.41, 0.92) p=0.018	0.32 (0.22, 0.47) p<0.0001	
6-year Subsequent Surgery (contralateral knee)	none vs. scope	scope						
	none vs. ACL reconstruction	ACL reconstruction						

Key: ADL = activities of daily living; sports/rec = sports and recreation; QOL = quality of life; BMI = body mass index; AC = articular cartilage; ACL = anterior cruciate ligament

Table 4

Significant Predictors for Worse Outcome 10 Years after ACL Reconstruction

IKDC	KOOS sports & recreation	KOOS QOL	Marx Activity Level
<ul style="list-style-type: none"> • Low baseline IKDC score • Low baseline activity level 	<ul style="list-style-type: none"> • Low baseline KOOS sports/recreation score 	<ul style="list-style-type: none"> • Low baseline KOOS QOL score • Low baseline activity level 	<ul style="list-style-type: none"> • Low baseline Marx score (low baseline activity level)
<ul style="list-style-type: none"> • Gender (female) 	<ul style="list-style-type: none"> • Higher age 	<ul style="list-style-type: none"> • Higher age 	<ul style="list-style-type: none"> • Higher age
<ul style="list-style-type: none"> • Higher BMI 	<ul style="list-style-type: none"> • Higher BMI 	<ul style="list-style-type: none"> • Higher BMI 	<ul style="list-style-type: none"> • Higher BMI
<ul style="list-style-type: none"> • Smoker 	<ul style="list-style-type: none"> • Smoker 		
<ul style="list-style-type: none"> • Lower education level 			<ul style="list-style-type: none"> • Lower education level
<ul style="list-style-type: none"> • Revision ACL reconstruction 	<ul style="list-style-type: none"> • Revision ACL reconstruction 	<ul style="list-style-type: none"> • Revision ACL reconstruction 	
<ul style="list-style-type: none"> • Medial meniscus procedure prior to index ACL reconstruction 	<ul style="list-style-type: none"> • Medial meniscus procedure prior to index ACL reconstruction 	<ul style="list-style-type: none"> • Medial meniscus procedure prior to index ACL reconstruction 	<ul style="list-style-type: none"> • Medial meniscus procedure prior to index ACL reconstruction
		<ul style="list-style-type: none"> • Lateral meniscus procedure prior to index ACL reconstruction 	
		<ul style="list-style-type: none"> • Lateral meniscectomy at the time of index ACL reconstruction 	
<ul style="list-style-type: none"> • AC medial pathology (Grades 3/4) 	<ul style="list-style-type: none"> • AC medial pathology (Grades 3/4) 	<ul style="list-style-type: none"> • AC medial pathology (Grades 2/3/4) 	
<ul style="list-style-type: none"> • AC lateral pathology (Grades 3/4) 	<ul style="list-style-type: none"> • AC lateral pathology (Grades 3/4) 	<ul style="list-style-type: none"> • AC lateral pathology (linear crack/fracture lines) 	
<ul style="list-style-type: none"> • AC patellofemoral pathology (Grades 3/4) 	<ul style="list-style-type: none"> • AC patellofemoral pathology (Grades 3/4) 	<ul style="list-style-type: none"> • AC patellofemoral pathology (Grades 3/4) 	<ul style="list-style-type: none"> • High-grade laxity

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Marx Activity Level	KOOS QOL	KOOS sports & recreation	IKDC
Subsequent surgery (ipsilateral knee)	•	Subsequent surgery (ipsilateral knee)	•
		Subsequent surgery (ipsilateral knee)	•
