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Predictors of Activity Level Two years after ACL Reconstruction: MOON ACLR Cohort Study

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Abstract

Objective—ACL deficient subjects are at risk of knee injury with cutting and pivoting activities; in accord, ACL reconstructions (ACLR) are performed to restore stability to allow for return to cutting and pivoting activities. The Marx activity level is a validated patient-reported measure to quantify the amount and frequency of running, cutting, decelerating, and pivoting performed. Our objective was to quantify activity level 2 yrs after ACLR and identify explanatory variables measured at baseline (demographics, concomitant meniscal/articular cartilage injuries and their treatment) associated with activity level at short-term follow-up (2 yrs).

Methods—In 2002, the multicenter consortium began enrolling subjects undergoing ACLR at six recruitment sites. This ongoing multicenter cohort study targets follow-up at 2, 6, and 10 years. The current study reports two-year follow-up of subjects enrolled in 2002. Participants in the multicenter ACLR cohort completed a series of validated, patient-oriented questionnaires that included activity level assessment. Follow-up questionnaires were collected by mail between 1/01/04 and 6/01/05 to assess changes. Measurement of intraarticular pathology, techniques of ACLR, and secondary procedures were recorded at baseline by participating surgeons. Multivariable proportional odds ordinal logistic regression was used to assess predictors of activity level after adjusting for baseline patient characteristics. Interquartile range (IQR) odds ratios (OR) are given for continuous variables, IQROR demonstrate the effect of increasing a baseline variable from its first quartile to its third quartile. The fitted model that used OR to

specify predicted probabilities of exceeding any activity level was translated into predicted mean activity level and is presented in a nomogram for more interpretability.

Results—Of the 446 subjects that underwent unilateral ACLR, follow-up was obtained on 393 (88%). The cohort is 56% male, median age 23 yrs. Median and IQR activity level was 12 (8–16) at baseline, and declined to 9 (3–13) at follow-up. After controlling for other baseline factors such as age, marital and student status, contralateral knee status, sport and competition level, and articular cartilage/meniscal injuries, the following factors were predictors of activity level at 2-year follow-up. High baseline activity level was associated with higher activity at 2 yrs (IQROR=3.8, 95% CI=2.0–7.4, $p<0.0001$), and lower baseline BMI (IQROR=1.37, 95% CI=1.04–1.82, $p=0.027$). The following baseline factors were associated with lower activity: female gender (OR=0.60, 95% CI=0.39–0.91, $p=0.015$); smoking within 6 months (IQROR=0.55, 95% CI=0.33–0.92, $p=0.023$); and revision ACLR (IQROR=0.41, CI=0.20–0.83, $p=0.014$).

Conclusions—(1) The proportion of subjects returning to the same or higher level of activity two years after ACLR was 45%, and evaluation of post treatment activity levels should control for patients' preoperative activity since this is a strong predictor of future activity. (2) Assuming physical activity is an important component of a healthy person, investigation of potential interventions to improve future activity could target modifiable exposures such as weight. (3) Further evaluation is needed to explore the association of gender and revision surgery on activity level following ACLR.

INTRODUCTION

Approximately 175,000 anterior cruciate ligament (ACL) reconstructions (ACLR) are performed annually with the intent of achieving two primary goals. First, is the short-term goal of improving knee function and stability such that patients may return to their preoperative cutting and pivoting activities. Second, is the mid-term goal of preventing secondary injury to the knee with a long-term goal of reducing the risk of post-traumatic arthritis. Ninety-eight percent of orthopaedic surgeons agree that strenuous activity is an indication for ACLR.¹⁶ While a minority of ACL deficient individuals do not develop functional instability ("copers"),^{8, 25} the majority (>90%) will experience episodes of knee instability during cutting and pivoting activities and consequently modify or decrease their desired activities to avoid secondary injury. Therefore, the short-term success of ACLR is, in large part, determined by restoring an athlete's ability to return to preoperative activity.

A validated scale quantifying the frequency of running, cutting, decelerating, and pivoting that is concise and easy to administer was developed and validated in 2000.¹⁷ The Marx Activity Scale evaluates activities that are difficult for those with ACL deficiency, and unlike the Tegner Activity Scale²⁷ and SARS (Sport Activity Rating Scale),²² more modern psychometric methods of development and validation were used to create this instrument. This self-administered scale targets clinically relevant activities rather than specific sports, and estimates the peak activity over the past year to account for variability related to seasonal trends in sports or injury. Hence, the Marx activity scale is a generalizable metric for use in sports medicine clinical research.

The Marx activity level is scored on a scale from 0–16. Activities are divided into four categories: running, cutting, decelerating, and pivoting. Each category is scored on a 5 point scale quantifying the frequency of participation as less than one time per month (0), one time per month (1), one time per week (2), 2 or 3 times per week (3), and 4 or more times in a week (4). The metric is reported as the sum of scores from the four categories ranging from 0–16. For example, a young competitive high school athlete practicing 4 times per week in football, basketball, or soccer would score a 16. Conversely, a recreational jogger 3 times per week would score a 3. Activity level in athletes or patients is one of the primary

outcomes for ACLR and is believed to be associated with future risk of failure and premature arthritis. Thus, we evaluated by multivariable modeling the independent predictors of two-year Marx activity level after ACLR in a prospective multicenter cohort study.

We hypothesized that preoperative activity level, age, revision versus primary ACLR, and concurrent articular cartilage injuries would be predictors of activity level two-years after ACLR; while graft choice, meniscus injuries and treatment, gender, and BMI would not be associated with activity level after ACLR.

MATERIALS AND METHODS

Study Design and Setting—A multicenter prospective longitudinal cohort design was implemented. In this ongoing multicenter cohort study, all subjects undergoing ACLR at six sites by eight physicians were targeted for enrollment. IRB approval was obtained from all participating centers. The recruitment period for the current study was between 01-01-2002 and 12-31-2002.

Participants—Subjects having unilateral primary or revision ACLR met inclusion criteria for study. Participants undergoing bilateral ACLR were excluded (Figure 1). Prior to publication it was determined that there was incomplete documentation of informed consent on 117 subjects. After conferring with the Institutional Review Board, contact was attempted for these subjects; 78 were re-consented, and the remaining 39 were removed from the final analysis.

The general study design requires that subjects preoperatively complete a 13-page form that includes the mechanism of injury, a series of validated patient-oriented outcome questionnaires (KOOS, Marx, IKDC), sports participation history, comorbidities, demographics, and prior surgery on either knee. The surgeons documented the examination under anesthesia, operative assessment and treatment of meniscus and articular cartilage injuries, and technical details of the ACLR procedure. Postoperatively, all subjects follow a standardized postoperative rehabilitation protocol. Follow-up data was obtained with a modified version of the same self-administered questionnaire completed at baseline, which was mailed to subjects at or around their two-year anniversary.

Baseline Patient Evaluation

Patients completed a 13-page form within two weeks of ACLR. Patient age, sex, height, weight, education, sport, date and mechanism of injury (non-traumatic, traumatic, contact, non-contact) were documented. In addition, previous ACLR or other knee surgery and patient symptoms such as the presence or absence of a “pop,” effusion, or instability at the time of injury and giving way and/or reinjury before ACLR were recorded as well. Current contact information from the patient and next of kin were documented for future follow-up. Also, the following validated patient-oriented outcome instruments were completed at baseline and a two-year follow-up: 1) Marx Activity Level; 2) Knee injury and Osteoarthritis Outcome Score (KOOS); and 3) International Knee Documentation Committee (IKDC) Subjective Knee Questionnaire.

After ACL reconstruction operating surgeons documented the following. Examination under anesthesia included an assessment of lower extremity alignment, patellar position and mobility, knee range of motion, presence or absence of an effusion, the Lachman exam recorded as side-to-side differences (instrumented result recorded if done), and endpoint quality (firm or soft). Anterior drawer (side-to-side difference in translation) and pivot shift

(grade 1 [glide], grade 2 [clunk], and grade 3 [gross]) were documented as well. The remaining knee ligaments were examined and the presence or absence of the following were detailed as side-to-side comparisons: posterior sag, posterior drawer, posterior drawer endpoint, medial and lateral joint opening at zero and 20 degrees, reverse pivot shift, internal and external rotation (at 30 and 90 degrees of flexion), and the presence of crepitus (patellofemoral and tibiofemoral compartments).

Intraoperative Details

Native ACL or ACL graft tears were documented as complete or partial (% fibers intact recorded). Medial collateral ligament (MCL) and lateral collateral complex tears (LCL) identified via arthroscopy or arthrotomy and subsequent treatment were noted. All articular lesions were first classified as degenerative or acute (traumatic) and depth was graded per a modified Outerbridge system.¹⁵ Within the three compartments of the knee (anterior, medial, lateral) the six articular cartilage surfaces (medial and lateral femoral condyles, medial and lateral tibial plateaus, the trochlea and patella) were classified as discrete locations as follows. Within the medial and lateral compartments, location and size of any articular cartilage lesion was estimated as percentage width (medial to lateral) and the number of degrees of the surface involved (anterior to posterior) for the femoral condyle, and as a percentage width both medial to lateral and anterior to posterior for the tibial plateau. For the anterior compartment, the location and size of patellar and trochlear lesions were recorded on a diagram that divided the surfaces into a 3 by 3 matrix (medial, central, lateral by proximal, middle, distal). Treatment, or lack thereof, of articular cartilage lesions was recorded for each of the six surfaces. Finally, the dimensions and treatment of any articular cartilage cracks were noted.

Medial and lateral meniscal tears were characterized by 1) location -- anterior vs. posterior and central vs. peripheral (central third, middle third, peripheral third or combination therein), 2) type (radial, oblique, longitudinal [vertical], bucket handle [displaced], horizontal, and complex), 3) length, and 4) degenerative changes (if present). The type and details of treatment for each meniscus tear were documented and included quantification of excision and/or repair technique and type of suture/implants.⁷

ACL reconstruction type was categorized as primary or revision. Graft type (autograft, allograft, or both) and graft source (bone-patellar tendon-bone, hamstring [semitendinosus, gracilis], iliotibial band, quadriceps tendon, Achilles tendon) were documented. Details of the ACLR technique that were captured included surgical exposure (arthroscopic one incision/two incision, open arthrotomy), notchplasty size if performed, femoral and tibial graft position (tunnel, over-the-top [OTT], modified OTT), methods of achieving femoral and tibial position and type of fixation. Graft excursion from zero to 90 degrees of flexion was documented.

Follow-up

Two-year patient follow-up was obtained by mail using a modified version of the same outcome questionnaire completed at baseline. This questionnaire documented any additional surgeries subsequent to the index ACLR performed in 2002. Further, all patients were queried by telephone regarding incident cases of additional knee surgeries. Patient follow-up was initiated on 01/01/04 and completed on 06/01/05.

Statistical Analyses

The purpose of the study was to determine activity level of subjects two years after ACLR and examine explanatory variables associated with return to activity. To that end, the Marx activity scale was used as the response variable, and the association of explanatory factors

recorded at baseline including pre-injury activity level was examined using a proportional odds ordinal logistic model.

Modeling Strategy—In general, an anti-parsimony approach was taken in order to generate a model as complex as the data would allow without overfitting using the ratio $p = m/10$ as the minimum acceptable ratio for reliable models (p = number of parameters in model; m = effective sample size). The effective sample size of the 2002 cohort was more than enough to consider the factors mentioned previously in our hypothesis, but not large enough to include all measured exposures in the model. The inclusion of additional variables as candidate predictors in the model was based on previously published studies (ie, ‘pop’ at the time of injury ²⁶) and expert opinion of the group.

Interquartile range odds ratios (IQROR) are given for continuous variables, which demonstrate the effect of increasing a baseline variable from its first quartile to its third quartile. The fitted model that used odds ratios to specify predicted probabilities of exceeding any activity level was translated into predicted mean activity level for more interpretability. We did not assume linearity of covariate effects but only assumed smoothed relationships, using restricted cubic regression splines. A nomogram was constructed to display the relationship of predictor variables and the mean Marx activity level at two years. A nomogram can be used to estimate the mean response (Marx activity level) for individual patients as well as show the relationship between the different predictor variables and how this affects the response.

For dealing with missing values of predictor variables we used multiple imputation incorporating predictive mean matching and flexible additive imputation models as implemented in the *aregImpute* function.² Data reduction methods used to preserve degrees of freedom in the model included pooling of low prevalence categories, variable grouping, and a redundancy analysis to identify colinear variables that could be deleted from the model. The latter was performed using the *redun* function² which uses hierarchical clustering (using squared Spearman rank correlation coefficients as the similarity matrix) to determine how well each variable can be predicted from the remaining independent variables ignoring the dependent variable. Statistical analysis was performed with free open source R statistical software (www.r-project.org).

RESULTS

Participants

From 01/01/02 to 12/31/02, 494 ACLR procedures were performed and enrolled in the study with follow-up obtained on 393 of the 446 subjects included in the final enrollment. The exclusion criteria and dropouts are summarized in a flow diagram (Figure 1).²⁹

Descriptive Data

The median age of the entire 2002 ACLR cohort was 23 years; baseline knee-related variables stratified by sex are summarized in Table 1 and baseline patient characteristics stratified by sex are listed in Table 2 (the number of non-missing values for each variable are listed). In general, injury in a contact sport, particularly playing football was more common in males, whereas females were younger with lower body mass indices (BMI) compared to males. The use of allograft was not uniform among the cohort (Table 3); allografts were more likely to be used in older subjects not injured in competitive sport, with accordingly lower baseline activity levels.

Patient-reported Outcomes

At baseline, the median Marx activity level (IQR) was 12 (8–16), and 2 years following ACLR the median activity level declined to 9 (3–13); the proportion of subjects that did not return to their pre-injury activity level was 55%. The baseline and two-year outcomes stratified by sex are presented in Table 4. There was one statistically significant sex difference found in the baseline KOOS knee-related quality of life subscale ($p=0.024$). The mean baseline and two-year KOOS scores are shown in Figure 2 with 95% confidence intervals. The relationship, at two-year follow-up, between the Marx activity level and activity level measured by the IKDC (Question 8 of the subjective IKDC form-‘What is the highest level of activity you can participate in on a regular basis?’) is summarized in Table 5. There was significant correlation between these two activity scales, spearman $\rho = 0.63$ ($p < 0.001$).

Data Reduction

For modeling purposes, the following categorical variables were reduced due to low prevalence categories. Articular cartilage variables were grouped by compartment (medial, lateral, anterior), and severity of chondromalacia was dichotomized into grade II chondromalacia or higher being positive for chondrosis in that compartment. Marital status categories widowed, separated, and divorced were collapsed into the ‘single’ category. Activity at injury was grouped into type of basketball, football, soccer, other sport, and non-sport injury. Status of the contralateral knee, taken from the IKDC, was collapsed into two categories; the normal ($n=322$) and nearly normal ($n=56$) categories were pooled, and the abnormal ($n=15$) and severely abnormal ($n=0$) were pooled.

Baseline candidate predictors considered for inclusion in the model were pre-injury Marx level, sport at injury, competition level, ethnicity, age, sex, marital status, baseline BMI, smoking status, age, student status, graft type, medial/lateral/anterior compartment chondrosis, reconstruction type, medial/lateral meniscus status, medial/lateral meniscus procedures, amount of medial/lateral meniscus excised, contralateral knee status, pop at injury, and site. To avoid overfitting the model, a redundancy analysis was performed that identified the following five variables as candidates for removal: 1) treatment of lateral meniscus tear, 2) medial meniscus status, 3) amount of medial meniscus excised, 4) living with spouse, and 5) age. Thus, the first four were not included in the model; however, age was retained in the model but treated as a linear term to preserve degrees of freedom. In a multicenter study it is important to consider site as a potential third variable, therefore, site was included in the initial model but it was not statistically significant ($p = 0.51$) and was removed.

Proportional odds ordinal logistic model

The final model includes the following baseline covariates: pre-injury Marx level, sport at injury, competition level, ethnicity, age, sex, marital status, BMI, smoking status, age, student status, graft type, medial/lateral/anterior compartment chondrosis, reconstruction type, lateral meniscus status, medial meniscus procedures, amount of lateral meniscus excised, contralateral knee status, and pop at injury.

Factors associated with higher activity levels at two years were higher baseline activity (IQROR=3.84, 95% CI=1.98–7.43, $p<0.0001$); lower baseline BMI (IQROR=1.37, 95% CI=1.04–1.82, $p=0.027$); higher level of competition ($p=0.027$), specifically, compared to those at a recreational level, competing at the high school level (OR=2.52, 95% CI=1.27–5.01) or college level (OR=4.23, 95% CI=1.85–9.66); and type of activity at injury ($p=0.023$). The following baseline factors were associated with lower activity level: female gender (OR=0.60, 95% CI=0.39–0.91, $p=0.015$); smoking within the last 6 months

(OR=0.55, 95% CI=0.33–0.92, $p=0.023$); and undergoing revision ACLR (OR=0.41, CI=0.20–0.83, $p=0.014$). A combined interaction test was performed using revision ACLR as an interaction term that yielded a Chi-square of 12.9 with 29 degrees of freedom ($p=0.9$). Figure 3 is a summary plot of the significant predictors in the final model, showing log odds ratios surrounded by 95% confidence intervals. The final model is presented as a nomogram in Figure 4, which can be used to predict activity level on future subjects by using the top line to get points for each individual predictor listed on the left hand column, summing these points, and then by transferring the sum to the total points axis a corresponding Predicted Activity Score can be estimated from the bottom line on the nomogram. Tables of point assignments by the levels of the individual predictors, and an example are provided in Appendix 1. For example, the formula for the model is included in Appendix 2.

DISCUSSION

Assuming the clinically important differences in the IKDC¹¹ and KOOS²⁴ are 11.5 and 8, respectively, the improvements observed in these outcomes at two years are clinically meaningful (Table 4). There was one statistically significant sex difference found in the KOOS knee-related quality of life subscale. Females had significantly higher knee-related quality of life compared to males at baseline, with median scores of 38 and 31, respectively ($p=0.024$). The difference, 7, is less than the minimum clinically meaningful difference of 8 points. This difference was no longer seen at two-year follow-up. The lack of clinically relevant sex differences in KOOS scores has been reported by others.^{9, 20} Paradowski et al. found significant sex differences in a population-based survey study among the KOOS pain, symptoms, and ADL function subscales, but these differences were only seen in subjects aged 55 to 74.²³ Hence, sex differences in the current study may be influenced by the relatively younger age of our cohort.

Reconstruction type, primary versus revision, is an important baseline exposure, and the regression model accounts for differences between them provided that the other baseline predictors in the model behave similarly between primaries and revisions. To determine if there were any statistical grounds for revision surgery being an effect modifier (i.e., tests the equality of effects of baseline variables on revisions vs. primaries) on any of the other variables in the model, a combined interaction test was performed which was not significant ($p=0.996$).

The results of this study indicating that most subjects (55%) do not return to their pre-injury activity level following ACLR is consistent with the findings of others that have shown subjects do not regain their pre-injury activity level following surgery.^{3–6, 10, 14, 18, 19, 21, 30} However, the current study utilized the Marx activity score, while most studies to date have utilized other activity measures such as the number returning to sport, or the Tegner scale. The Marx activity scale was used to measure activity in this cohort because it was designed as a self-reported measure of specific functions that are potentially challenging for those with ACL deficiency, and unlike the Tegner scale, an assessor-reported metric, it quantifies how often activities are performed. The Marx activity scale is designed to avoid ceiling effects such that only regular participation in competitive athletics requiring cutting, pivoting, and decelerating will result in a score of 12–16. However, an aerobically fit person participating only in sagittal-plane activities such as running two to three times a week would have a Marx activity score of three. Thus a lower Marx does not necessarily equate to a lack of physical activity or fitness.

The analysis cannot definitively answer why 55% of subjects did not return to their pre-injury activity level. Factors presumably related to functional status of the knee such as the condition of the articular cartilage and menisci, as well as normalcy of the contralateral

knee, were included in the model and not predictive of activity level at two years. The proportion of subjects that reduce their activity level due to knee function ranges 13–70% among published studies.^{3, 6, 10, 13, 14, 19, 30}

Possible alternative explanations other than knee function include fear of re-injury, self-efficacy, graduation from high school or college, other lifestyle and/or socioeconomic status changes commensurate with adulthood social transitions leading to increased work and family responsibilities. Patient's pre-operative perceived self-efficacy of knee function has been shown to predict activity level one year following ACLR,²⁸ however, self-efficacy was not measured in the current study. Several authors have reported reduced activity following ACLR due to social or family reasons.^{4, 10, 19} Kostogiannis et al. found the median Tegner activity level at the time of ACL injury to be 7 (range, 3–9), at 1 year the median score decreased to 6 (range, 2–9), was similar at 3 years, median Tegner was 6 (range, 3–9); however, at 15 years the median score decreased to 4 (range, 1–7) $p < 0.001$.¹² The authors speculated that the decrease in activity observed in this long-term follow-up study might be a natural adaptation to aging indicative of evolving stages of life. Andersson-Molina et al.¹ reported similar declines in activity level at 14-year follow-up between normal control subjects with no history of knee injury or surgery matched to post meniscectomy subjects on age, sex, and baseline Tegner activity level.

There is little research regarding fear of re-injury as a cause of reduced activity level following ACL injury.^{4, 10, 14, 19} Studies to date often do not report reasons for not returning to pre-injury activity or sport. The few studies that include patient-reported reasons for a decline in activity level have implicated fear of re-injury and diminished performance as psychological barriers to returning to the pre-injury activity level.^{4, 14, 19} Carey et al. reported 21% of running backs and wide receivers do not return to the National Football League after ACL injury, and of those that do return, it is usually at a lesser performance level,⁵ however, they did not include data from the athletes' perspective in this study. The possible role of fear of re-injury and its relationship to decreased athletic performance in the latter study is unclear.

Overall, the strongest predictor of activity level at 2 years was the baseline activity level. This finding is consistent with Tohomee et al.'s finding that the pre-injury Tegner score was a significant predictor of the Tegner at one-year follow-up ($p = 0.002$).²⁸ Hence, there is growing evidence that the evaluation of post-surgical activity levels, particularly after ACLR, should control for preoperative activity. Assuming physical activity is an important component of a healthy person, modifiable factors such as body weight may warrant further investigation as targets for future interventions. Further evaluation is needed to explore the association of gender and revision procedures on activity level following ACLR. Webb et al. found significantly fewer men (36%) than women (54%) not returning to pre-injury activity level at two years following ACLR,³⁰ however, at five-year follow-up the difference among men (59%) and women (79%) was no longer statistically significant ($p = 0.21$).⁶ Frobell et al. found in a cross-sectional study that older age, female sex, and lower competition level were associated with lower self-reported activity level, while BMI was not associated with activity level using linear regression models.⁹ While female sex and lower competition level are consistent with our results, the inclusion of more explanatory variables in our regression models, as well as the longitudinal design of the current study may explain the differences seen regarding BMI and age. Longer-term longitudinal follow-up of this cohort could explore further time trends in predictors of activity level.

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Appendix 1

Example (all patient characteristics with corresponding points are underlined): A 15 year old nonsmoker white male high school student with a baseline marx of 16 injured in soccer without an associated ‘pop’, that underwent a primary ACLR using autograft ...

Sum of points of individual predictors:

$28 + 85 + 61 + 100 + 52 + 49 + 23 + 12 + 0 + 28 + 5 + 0 + 32 + 30 + 0 + 0 + 3 + 50 + 54 + 32 = 644$, which would correspond to a predicted activity score of 15.

Sex	Points
male	28
female	0

Baseline Marx	Points
0	0

Baseline Marx	Points
2	0
4	2
6	5
8	13
10	24
12	41
14	62
16	85

Age	Points
10	67
15	61
20	55
25	49
30	43
35	37
40	30
45	24
50	18
55	12
60	6
65	0

Baseline BMI	Points
15	100
20	86
25	71
30	57
35	43
40	29
45	14
50	0

Ethnicity	Points
OTHER	35
Black	0
White	52

Reconstruction Type	Points
primary	49
revision	0

Graft Type	Points
Autograft	23
Allograft	0
Pop at Injury	Points
no	12
yes	0
Contralateral Knee	Points
Normal	0
Abnormal	20
Medial Chondrosis	Points
No	28
Yes	0
Anterior Chondrosis	Points
No	5
Yes	0
Lateral Chondrosis	Points
No	0
Yes	13
Medial Meniscus Tx	Points
Normal	32
Repair	0
Excision	29
Lateral Meniscus Status	Points
Normal	17
Partial tear	30
Complete tear	0
Lateral Men Excision	Points
Normal	0
<33%	13
>50%	1
Marital Status	Points
Single	0

Marital Status	Points
Married	11

Student	Points
no	0
yes	3

Level of Competition	Points
None	4
Recreational	0
Amateur (team or club)	37
High school	50
College	78
Pro	14

Activity at Injury	Points
Other	16
Basketball	47
Football	38
Soccer	54
Non-sport	0

Smoking Status	Points
Within 6m	0
Not within 6m	32

Total Points	Predicted Activity Score
250	1
298	2
330	3
356	4
380	5
401	6
422	7
443	8
463	9
484	10
506	11
530	12
556	13
588	14
635	15

Appendix 2

$$\text{Prob}\{2 \text{ yr } Marx \geq j\} = \frac{1}{1 + \exp(-\alpha_j - X\beta)},$$

where

$\hat{a}_1 = 3.025$	$\hat{a}_2 = 2.702$	$\hat{a}_3 = 2.325$	$\hat{a}_4 = 1.948$
$\hat{a}_5 = 1.602$	$\hat{a}_6 = 1.267$	$\hat{a}_7 = 1.042$	$\hat{a}_8 = 0.764$
$\hat{a}_9 = 0.307$	$\hat{a}_{10} = -0.039$	$\hat{a}_{11} = -0.231$	$\hat{a}_{12} = -0.411$
$\hat{a}_{13} = -1.246$	$\hat{a}_{14} = -1.521$	$\hat{a}_{15} = -1.627$	$\hat{a}_{16} = -1.756$

$$\begin{aligned} \widehat{X\beta} = & +0.00088 Marx_{baseline} + 0.00044(Marx_{baseline})_+^3 - 0.0012(Marx_{baseline} - 10)_+^3 + 0.0007(Marx_{baseline} - 16)_+^3 - 0.053age \\ & - 0.053 BMI_{baseline} - 0.52\{female\} - 0.9\{revision ACLR\} - 0.22\{pop at injury\} + 0.38\{abnormal contralateral knee\} \\ & - 0.51\{medial chondrosis\} - 0.096\{anterior chondrosis\} + 0.25\{lateral chondrosis\} - 0.44\{allo graft\} + 0.06\{student\} \\ & - 0.0601\{medial meniscal repair\} - 0.062\{medial meniscus excision\} + 0.25\{partial lateral meniscus tear\} \\ & - 0.32\{complete lateral meniscus tear\} + 0.27\{lateral meniscus excision < 33\%\} + 0.019\{lateral meniscus excision > 50\%\} \\ & - 0.64\{black\} + 0.32\{white\} + 0.20\{married\} - 0.074\{recreational level\} + 0.606\{amateur level\} + 0.852\{high school level\} \\ & + 1.368\{college level\} + 0.184\{professional level\} + 0.57\{basketball injury\} + 0.42\{football injury\} + 0.72\{soccer injury\} \\ & - 0.29\{nonsport injury\} + 0.6\{no smoking within 6 months\} \end{aligned}$$

$\{categorical variable\} = 1$ if subject is in the group specified in bracket, 0 otherwise $(x)_+ = x$ if $x > 0$, 0 otherwise

Figure 1.
Flow diagram – 2002 Multicenter ACLR Cohort.

Figure 2. KOOS Profile with 0.95 Confidence Limits comparing baseline (t0) and 2 year (t2) scores for pain, symptoms, ADL function, sports & recreation, and knee-related quality of life subscales.

Figure 3.

Summary plot of key predictors of Marx activity level at 2 years adjusted for all variables in the final model. Vertical black ticks indicate the log odds ratio (for continuous predictors the IQROR is given), which can be read off the top horizontal axis, surrounded by the 95% confidence intervals in grey that should not overlap the vertical dashed line indicating zero if there is a statistically significant effect. For example, the effect of lowering BMI from its third quartile (28) to its first quartile (22) is to raise the mean two-year activity score by 1.4 points (95% CI=1.04–1.82), while those injured in soccer have a mean two-year activity score 2.8 points higher than subjects with non-sport injuries (95% CI= 1.3–5.7).

Figure 4.

Nomogram for the model predicting Marx activity level 2 years after ACLR. Use the top line to get points for each individual predictor listed in the left hand column. Manually sum these points, and then transfer the sum to the total points axis to determine the corresponding Predicted Activity Score on the bottom line of the nomogram.

Table 1

Baseline knee-related characteristics stratified by sex. (Chondrosis = the presence of > grade 2 chondromalacia using the modified Outerbridge classification in the respective compartment at the time of index ACLR.) There are no missing values for these variables.

	male		female		Combined	
	N = 222	N = 171	N = 171	N = 171	N = 393	N = 393
Reconstruction Type : primary	199 90%	162 95%	162 95%	162 95%	361 92%	361 92%
revision	23 10%	9 5%	9 5%	9 5%	32 8%	32 8%
Surgical Exposure : Two-incision	71 32%	45 26%	45 26%	45 26%	116 30%	116 30%
Endoscopic	150 68%	126 74%	126 74%	126 74%	276 70%	276 70%
Arthrotomy	1 0%	0 0%	0 0%	0 0%	1 0%	1 0%
Medial Meniscus Status : normal	137 62%	115 67%	115 67%	115 67%	252 64%	252 64%
partial tear	18 8%	8 5%	8 5%	8 5%	26 7%	26 7%
complete tear	67 30%	48 28%	48 28%	48 28%	115 29%	115 29%
Lateral Meniscus Status : normal	118 53%	94 55%	94 55%	94 55%	212 54%	212 54%
partial tear	30 14%	26 15%	26 15%	26 15%	56 14%	56 14%
complete tear	74 33%	51 30%	51 30%	51 30%	125 32%	125 32%
Medial Chondrosis : No	178 80%	138 81%	138 81%	138 81%	316 80%	316 80%
Yes	44 20%	33 19%	33 19%	33 19%	77 20%	77 20%
Lateral Chondrosis : No	175 79%	145 85%	145 85%	145 85%	320 81%	320 81%
Yes	47 21%	26 15%	26 15%	26 15%	73 19%	73 19%
Anterior Chondrosis : No	173 78%	144 84%	144 84%	144 84%	317 81%	317 81%

	male	female	Combined
	N = 222	N = 171	N = 393
Yes			
	49 22%	27 16%	76 19%
MCL Status : normal			
grade i	191 86%	153 89%	344 88%
grade ii	18 8%	5 3%	23 6%
grade iii	10 5%	6 4%	16 4%
	3 1%	7 4%	10 3%
LCL Status : normal			
	209 94%	167 98%	376 96%
grade i	3 1%	2 1%	5 1%
grade ii	2 1%	0 0%	2 1%
grade iii	8 4%	2 1%	10 3%
Contralateral Knee : Normal			
	211 95%	167 98%	378 96%
Abnormal	11 5%	4 2%	15 4%

Table 2

Baseline Patient Characteristics stratified by Sex

	N	male N = 222	female N = 171	Combined N = 393
Age	393	18 26.36 (28±11)	17 20.33 (25±11)	17 23.35 (27±11)
Baseline BMI	386	23.7 25.8 28.4 (26.4± 4.3)	21.1 23.0 26.5 (24.3± 4.5)	22.3 24.9 28.0 (25.5± 4.5)
Activity at Injury	393			
Other		19% $\frac{42}{222}$	36% $\frac{61}{171}$	26% $\frac{103}{393}$
Basketball		23% $\frac{52}{222}$	25% $\frac{43}{171}$	24% $\frac{95}{393}$
Football		23% $\frac{50}{222}$	5% $\frac{9}{171}$	15% $\frac{59}{393}$
Soccer		16% $\frac{36}{222}$	20% $\frac{35}{171}$	18% $\frac{71}{393}$
Non-sport		19% $\frac{42}{222}$	13% $\frac{23}{171}$	17% $\frac{65}{393}$
Competition Level	388			
None		15% $\frac{32}{218}$	13% $\frac{22}{170}$	14% $\frac{54}{388}$
Recreational		34% $\frac{74}{218}$	27% $\frac{46}{170}$	31% $\frac{120}{388}$
Amateur team/club		17% $\frac{37}{218}$	18% $\frac{31}{170}$	18% $\frac{68}{388}$
High School		21% $\frac{46}{218}$	26% $\frac{44}{170}$	23% $\frac{90}{388}$
College/Pro		13% $\frac{29}{218}$	16% $\frac{27}{170}$	14% $\frac{56}{388}$
Smoking Status	390			
current		12% $\frac{27}{219}$	9% $\frac{16}{171}$	11% $\frac{43}{390}$
quit < 6m		11% $\frac{24}{219}$	7% $\frac{12}{171}$	9% $\frac{36}{390}$
quit > 6m		3% $\frac{6}{219}$	2% $\frac{3}{171}$	2% $\frac{9}{390}$
never		74% $\frac{162}{219}$	82% $\frac{140}{171}$	77% $\frac{302}{390}$

	N	male N = 222	female N = 171	Combined N = 393
Ethnicity	388			
OTHER		9% $\frac{19}{218}$	4% $\frac{6}{170}$	6% $\frac{25}{388}$
black		5% $\frac{11}{218}$	7% $\frac{12}{170}$	6% $\frac{23}{388}$
white		86% $\frac{188}{218}$	89% $\frac{152}{170}$	88% $\frac{340}{388}$

a b c represent the lower quartile *a*, the median *b*, and the upper quartile *c* for continuous variables, $\bar{x} \pm s$ represents $\bar{X} \pm 1$ SD.
N is the number of non-missing values.

Table 3

Baseline Characteristics by Graft Type

	N	Autograft N = 332	Allograft N = 61
Activity at Injury	393		
Other		86 26% 332	17 28% 61
Basketball		80 24% 332	15 25% 61
Football		51 15% 332	8 13% 61
Soccer		66 20% 332	5 8% 61
Non-sport		49 15% 332	16 26% 61
Competition Level	388		
None		34 10% 327	20 33% 61
Recreational		101 31% 327	19 31% 61
Amateur team/club		61 19% 327	7 11% 61
High School		81 25% 327	9 15% 61
College/Pro		50 15% 327	6 10% 61
Age	393	17 21 33 (26±11)	22 32 40 (33±12)
Sex	393		
male		182 55% 332	40 66% 61
female		150 45% 332	21 34% 61
Reconstruction Type	393		
primary		316 95% 332	45 74% 61
revision		16 5% 332	16 26% 61

	N	Autograft N = 332	Allograft N = 61
Baseline Marx	385	9.0 13.0 16.0 (11.6± 5.1)	4.0 10.0 13.5 (8.8± 5.7)
Baseline IKDC Activity Level	390		
unable		13 4% ³²⁹	12 20% ⁶¹
light activity		177 54% ³²⁹	34 56% ⁶¹
moderate activity		95 29% ³²⁹	10 16% ⁶¹
strenuous activity		8 2% ³²⁹	3 5% ⁶¹
very strenuous activity		36 11% ³²⁹	2 3% ⁶¹

a b c represent the lower quartile *a*, the median *b*, and the upper quartile *c* for continuous variables. *x* ± *s* represents $\bar{X} \pm 1$ SD.
N is the number of non-missing values.

Table 4

Baseline and Follow-up Outcomes by Sex

	N	male N = 222	female N = 171	Combined N = 393	Test Statistic
Baseline Marx	385	8.0 12.0 16.0 (11.1± 5.3)	8.0 13.0 16.0 (11.2± 5.4)	8.0 12.0 16.0 (11.2± 5.3)	$F_{1,383} = 0.43, P = 0.51$
Marx at 2y	393	4.0 9.0 14.0 (8.7± 5.6)	3.0 9.0 13.0 (8.2± 5.7)	3.0 9.0 13.0 (8.5± 5.6)	$F_{1,391} = 0.62, P = 0.43$
Baseline IKDC score	388	38 51 66 (51±19)	41 53 64 (53±16)	40 53 65 (52±18)	$F_{1,386} = 0.69, P = 0.41$
IKDC score at 2y	387	72 84 92 (79±18)	74 83 91 (80±15)	74 84 92 (80±17)	$F_{1,385} = 0.01, P = 0.93$
Baseline KOOS ADL	388	71 87 97 (80±20)	76 88 96 (85±15)	72 88 97 (82±18)	$F_{1,386} = 1.4, P = 0.23$
KOOS ADL at 2y	393	92.6 98.5 100.0 (92.6± 13.1)	92.6 98.5 100.0 (94.0± 9.2)	92.6 98.5 100.0 (93.2± 11.6)	$F_{1,391} = 0.01, P = 0.94$
Baseline KOOS KRQoL	393	19 31 50 (34±20)	25 38 50 (39±20)	19 38 50 (36±20)	$F_{1,391} = 5.1, P = 0.024$
KOOS KRQoL at 2y	393	56 75 88 (70±25)	62 81 88 (73±22)	62 75 88 (71±24)	$F_{1,391} = 1.4, P = 0.23$
Baseline KOOS SpisRec	377	20 50 75 (48±31)	30 52 75 (53±29)	25 50 75 (50±30)	$F_{1,375} = 2.1, P = 0.15$
KOOS SpisRec at 2y	393	65 85 95 (77±23)	70 85 95 (80±20)	70 85 95 (79±22)	$F_{1,391} = 1.2, P = 0.28$
Baseline KOOS Symptoms	391	54 68 82 (67±20)	57 71 82 (70±17)	57 68 82 (68±19)	$F_{1,389} = 1.6, P = 0.21$
KOOS Symptoms at 2y	393	75 86 93 (81±16)	75 86 93 (82±16)	75 86 93 (81±16)	$F_{1,391} = 0.02, P = 0.9$
Baseline KOOS Pain	392	58 75 89 (73±20)	63 78 89 (75±17)	61 78 89 (74±19)	$F_{1,390} = 0.97, P = 0.33$
KOOS Pain at 2y	393	83 92 97 (87± 15)	86 94 100 (90± 13)	83 92 97 (88± 14)	$F_{1,391} = 3.6, P = 0.06$

a b c represent the lower quartile *a*, the median *b*, and the upper quartile *c* for continuous variables. *x* ± *s* represents $\bar{X} \pm 1$ SD.

N is the number of non-missing values.

Test used:

Wilcoxon test

Table 5

Marx Activity Scores stratified by IKDC Activity Level

	unable	light activity	moderate activity	strenuous activity	very strenuous activity	Test Statistic
	N = 10	N = 42	N = 89	N = 85	N = 167	
Marx at 2y	0.0 1.5 6.8 (4.0± 5.3)	0.0 0.0 4.0 (2.5± 4.3)	2.0 5.0 8.0 (5.5± 4.7)	4.0 8.0 11.0 (7.6± 4.7)	10.0 13.0 16.0 (12.4± 4.0)	$F_{4,388} = 66, P < 0.001$

a b c represent the lower quartile *a*, the median *b*, and the upper quartile *c* for continuous variables. *x* ± *s* represents $\bar{X} \pm 1$ SD.

Test used:

Kruskal-Wallis test