PODCAST 5-in-5

Surgical Predictors of Clinical Outcomes After Revision Anterior Cruciate Ligament Reconstruction

The MARS Group*†
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Background: Revision anterior cruciate ligament (ACL) reconstruction has been documented to have worse outcomes compared with primary ACL reconstruction.

Hypothesis: Certain factors under the control of the surgeon at the time of revision surgery can both negatively and positively affect outcomes.

Study Design: Case-control study; Level of evidence, 3.

Methods: Patients undergoing revision ACL reconstruction were identified and prospectively enrolled between 2006 and 2011. Data collected included baseline demographics, intraoperative surgical technique and joint disorders, and a series of validated patient-reported outcome instruments (International Knee Documentation Committee [IKDC] subjective form, Knee Injury and Osteoarthritis Outcome Score [KOOS], Western Ontario and McMaster Universities Osteoarthritis Index [WOMAC], and Marx activity rating scale) completed before surgery. Patients were followed up for 2 years and asked to complete an identical set of outcome instruments. Regression analysis was used to control for age, sex, body mass index (BMI), activity level, baseline outcome scores, revision number, time since last ACL reconstruction, and a variety of previous and current surgical variables to assess the surgical risk factors for clinical outcomes 2 years after revision ACL reconstruction.

Results: A total of 1205 patients (697 male [58%]) met the inclusion criteria and were successfully enrolled. The median age was 26 years, and the median time since their last ACL reconstruction was 3.4 years. Two-year follow-up was obtained on 82% (989/1205). Both previous and current surgical factors were found to be significant contributors toward poorer clinical outcomes at 2 years. Having undergone previous arthrotomy (nonarthroscopic open approach) for ACL reconstruction compared with the 1-incision technique resulted in significantly poorer outcomes for the 2-year IKDC ($P = .037$; odds ratio [OR], 2.43; 95% CI, 1.05-5.88) and KOOS pain, sports/recreation, and quality of life (QOL) subscales ($P \leq .05$; OR range, 2.38-4.35; 95% CI, 1.03-10.00). The use of a metal interference screw for current femoral fixation resulted in significantly better outcomes for the 2-year KOOS symptoms, pain, and QOL subscales ($P \leq .05$; OR range, 1.70-1.96; 95% CI, 1.00-3.33) as well as WOMAC stiffness subscale ($P = .041$; OR, 1.75; 95% CI, 1.02-3.03). Not performing notchplasty at revision significantly improved 2-year outcomes for the IKDC ($P = .013$; OR, 1.47; 95% CI, 1.08-1.99), KOOS activities of daily living (ADL) and QOL subscales ($P \leq .04$; OR range, 1.40-1.41; 95% CI, 1.03-1.93), and WOMAC stiffness and ADL subscales ($P \leq .04$; OR range, 1.41-1.49; 95% CI, 1.03-2.05). Factors before revision ACL reconstruction that increased the risk of poorer clinical outcomes at 2 years included lower baseline outcome scores, a lower Marx activity score at the time of revision, a higher BMI, female sex, and a shorter time since the patient's last ACL reconstruction. Prior femoral fixation, prior femoral tunnel aperture position, and knee flexion angle at the time of revision graft fixation were not found to affect 2-year outcomes in this revision cohort.

Conclusion: There are certain surgical variables that the physician can control at the time of revision ACL reconstruction that can modify clinical outcomes at 2 years. Whenever possible, opting for an anteromedial portal or transtibial surgical exposure, choosing a metal interference screw for femoral fixation, and not performing notchplasty are associated with significantly better 2-year clinical outcomes.

Keywords: anterior cruciate ligament; revision ACL reconstruction; outcomes; surgical factors; surgical approach; tunnel position; ACL fixation

Revision anterior cruciate ligament (ACL) reconstruction has been documented to have worse outcomes compared with primary ACL reconstruction.‡ The Multicenter ACL

‡References 1-3, 8-10, 12, 20, 22, 23, 25, 26.

The American Journal of Sports Medicine, Vol. 45, No. 11
DOI: 10.1177/0363546517712952

Revision Study (MARS) group has identified several contributing factors for outcomes, including graft choice, previous lateral meniscectomy, and trochlear groove chondrosis.[14,15] Other factors remain unknown. Numerous factors remain beyond the control of the patient or the surgeon with regard to revision ACL reconstruction. Fortunately, some factors can be controlled by the surgeon when planning reconstruction.

The ACL graft choice at the time of revision reconstruction has been shown to affect outcomes.[5,11,14] In a previous study by the MARS group, it was demonstrated that the use of an autograft (compared with an allograft) is associated with an improved return to sports and decreased risk of graft reruptures by 2.78 times.[14] Additional factors such as surgical approach (eg, anteromedial portal, transtibial, 2-incision, arthrotomy), tunnel choice (new, old, or “blended,” defined as the combination of old and new tunnels), bone grafting, and fixation choice may allow options for the operating surgeon. The purpose of this study was to determine if either previous or current surgical factors noted at the time of revision ACL reconstruction predicted activity level, sports function, and osteoarthritis symptoms at 2-year follow-up. Our hypothesis was that surgical factors under the control of the surgeon (eg, surgical approach, tunnel choice, notchplasty, bone grafting, fixation choice) could both negatively and positively affect revision ACL reconstruction outcomes.

METHODS

Setting and Study Population

The MARS group was assembled with the aims of determining what affects outcomes in a revision ACL reconstruction setting and identifying potentially modifiable factors that could improve these outcomes.[6,16,24,27] This collaboration consists of a group of 83 sports medicine fellowship–trained surgeons across 52 sites. These surgeons are a near equal mix of academic and private practitioners. After obtaining approval from the respective institutional review boards, this multicenter consortium began patient enrollment in 2006 and ended in 2011, during which time 1205 patients undergoing revision ACL reconstruction were enrolled in this prospective longitudinal cohort. The study enrolled patients undergoing revision of a previously failed ACL reconstruction (as identified by a clinical examination, imaging, or arthroscopic surgery) who agreed to participate, signed an informed consent form, and completed a series of patient-reported outcome instruments. Indications for revision ACL reconstruction included functional instability, abnormal laxity testing findings, or magnetic resonance imaging indicating a graft tear. Multiligament reconstruction was excluded. Ligament injuries not requiring reconstruction (ie, medial collateral ligament) were included. Surgeon inclusion criteria included maintenance of institutional review board approval, completion of a training session that integrated articular cartilage and meniscus agreement studies, review of the study design and patient inclusion criteria, and review of the surgeon questionnaire.[18] The surgical technique was at the discretion of the treating surgeon.

Data Sources and Measurement

After giving informed consent, the patient filled out a 13-page questionnaire that included questions regarding demographics, sports participation, injury mechanism, comorbidities, and knee injury history, as previously described.[14,16] Within this questionnaire, each participant also completed a series of validated general and knee-specific outcome instruments, including the Knee Injury and Osteoarthritis Outcome Score (KOOS), the International Knee Documentation Committee (IKDC) subjective form, and the Marx activity rating scale. Contained within the KOOS was the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC). Surgeons filled out a 42-page questionnaire that included their impression of the cause of the previous failure, physical examination findings, surgical technique utilized, intra-articular findings, and surgical management of meniscal and chondral damage.

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 Tele-Form software (Cardiff Software) utilizing 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 before data analysis.

Patient Follow-up

Two-year patient follow-up was completed by mail with readministration of the same questionnaire as the one that they completed at baseline. Patients were also contacted by telephone to determine whether any subsequent surgery had been performed on either knee since their initial revision ACL reconstruction. If so, operative reports were obtained, whenever possible, to verify injured structures and treatment.

Statistical Analysis

To describe our patient sample, we summarized continuous variables as percentiles (ie, 25th, 50th, and 75th) and categorical variables as frequencies and percentages. Multivariable regression analyses were performed to examine which baseline risk factors were independently associated with each outcome variable. The primary outcome variables of interest were

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One or more of the authors has declared the following potential conflict of interest or source of funding: This study received funding from the American Orthopaedic Society for Sports Medicine, Smith & Nephew, National Football League Charities, and the Musculoskeletal Transplant Foundation. This project was partially funded by grant No. 5R01-AR060846 from the National Institutes of Health/National Institute of Arthritis and Musculoskeletal and Skin Diseases.

the 2-year outcome scores of the KOOS, IKDC, WOMAC, and Marx activity rating scale. These primary outcome variables were all treated as continuous, and as such, ordinal logistic regression models were used. All models controlled for age, sex, body mass index (BMI), activity level, baseline outcome scores, revision number, time from previous ACL reconstruction, and a variety of previous and current surgical variables (including graft choice and meniscal and chondral damage) to assess the surgical risk factors for clinical outcomes 2 years after revision surgery. Per the number of levels, categorical variables were fit according to their degrees of freedom (ie, n – 1). To stay within the allowable degrees of freedom, each continuous variable was fit as a linear effect, as there was little or no evidence of a nonlinear relationship with a P value $\leq$.05 for the nonlinear test. Statistical analysis was performed using open-source R statistical software (version 3.0.3; www.r-project.org).

RESULTS

Study Population and Follow-up

A total of 1205 patients (697 male [58%]) met the inclusion criteria and were successfully enrolled. The median age was 26 years, and median time since the patients' last ACL reconstruction was 3.4 years. Baseline characteristics of the cohort are summarized in Table 1. At 2 years, questionnaire follow-up was obtained on 82% (989/1205).

Influence of Surgical Factors on 2-Year Outcomes

A variety of surgeon-based surgical factors predicted outcomes. Both previous as well as current surgical factors were found to be associated with poorer outcomes at 2 years (Table 2).

Surgical Approach and Tunnel Choice. A history of arthrotomy at the time of the previous reconstruction (compared with the 1-incision technique) was associated with significantly poorer outcomes for the 2-year IKDC (P = .037; odds ratio [OR], 2.43; 95% CI, 1.05-5.88) and KOOS pain, sports/recreation, and quality of life (QOL) subscales (P $\leq$ .05; OR range, 2.38-4.35; 95% CI, 1.03-10.00). In particular, patients having undergone previous arthrotomy at their earlier reconstruction were 4.35 times more likely to have a poorer KOOS QOL outcome at 2 years compared with patients who had undergone a previous 1-incision approach (P = .001). Patients having a history of double femoral tunnels were 3.13 times more likely to have a poorer KOOS QOL outcome at 2 years compared with patients who had a single femoral tunnel (P = .027). A prior tibial tunnel aperture position defined as "ideal" in position and size by the participating MARS surgeon at the time of revision surgery was associated with significantly worse 2-year clinical outcomes on nearly all instruments (IKDC; pain, activities of daily living [ADL], sports/recreation, and QOL subscales; WOMAC stiffness, pain, and ADL subscales) when compared with a tibial tunnel aperture position defined as "ideal in both position and size but enlarged tunnels."

At revision, surgical exposure with the 2-incision technique had worse Marx activity scores (P = .029) and KOOS symptoms subscores (P = .028) compared with anteromedial portal femoral tunnel drilling. The transtibial versus anteromedial approach was not associated with outcomes. Choosing to utilize a previous femoral tunnel that was deemed to be in the optimum position versus drilling an entirely new tunnel was associated with worse KOOS QOL subscores (P = .025).

Choosing to drill a second tibial tunnel versus utilizing the previous tibial tunnel position was associated with significantly worse KOOS ADL (P = .026) and WOMAC ADL subscores at 2 years (P = .026). In particular, a patient needing a second tibial tunnel drilled had a 3.45 times higher likelihood of having poorer 2-year KOOS ADL and WOMAC ADL subscores when compared with the tibial tunnel being in the optimum position at the time of revision surgery.

Patients who underwent notchplasty at the time of revision had worse IKDC scores, KOOS ADL and QOL subscores, and WOMAC stiffness and ADL subscores. Revision without notchplasty had significantly improved 2-year outcomes for the IKDC (P = .013; OR, 1.47; 95% CI, 1.08-1.99), KOOS ADL and QOL subscales (P $\leq$ .04; OR range, 1.40-1.41; 95% CI, 1.03-1.93), and WOMAC stiffness and ADL subscales (P $\leq$ .04; OR range, 1.41-1.49; 95% CI, 1.03-2.05).

Fixation Choice. Using a metal interference screw for current revision femoral fixation (compared with bioabsorbable interference screws, cross pins, or a combination of fixation devices) was associated with significantly better outcomes for the 2-year KOOS symptoms, pain, and QOL subscales (P $\leq$ .05; OR range, 1.70-1.96; 95% CI, 1.00-3.33) as well as WOMAC stiffness subscale (P = .041; OR, 1.75; 95% CI, 1.02-3.03). Similarly, using a metal interference screw for current revision tibial fixation (compared with using a combination of fixation devices) was associated with significantly better IKDC scores (P = .017) and WOMAC stiffness subscores (P = .013).

Biology. Femoral tunnel bone grafting, either 1- or 2-staged, was associated with worse Marx activity scores at 2 years (P = .048; OR, 2.04; 95% CI, 1.00-4.17). Conversely, patients who required tibial tunnel bone grafting (1- or 2-staged) actually reported improved outcomes for the KOOS pain (P = .046) and WOMAC pain (P = .004) subscales. The utilization of a biological enhancement agent (ie, platelet-rich plasma, mesenchymal stem cells) was associated with worse Marx activity scores at 2 years (P = .025).

In summary, the most consistent surgical factors associated with better outcomes in patients undergoing revision were prior surgical approach, prior tibial tunnel aperture position, current femoral fixation, and not performing notchplasty. Conversely, prior femoral fixation, prior femoral tunnel aperture position, and the knee flexion angle at the time of graft fixation were not found to be associated with 2-year outcomes in this revision cohort.

Influence of Patient Characteristics on 2-Year Outcomes

Lower baseline outcome scores predicted worse 2-year outcomes for the Marx activity rating scale, all KOOS

TABLE 1
Baseline Characteristics of Cohort[a]

	Value
Patient demographics	
Sex	
Male	697 (58)
Female	508 (42)
Age, median (IQR), y	26 (20-35)
Body mass index, median (IQR), kg/m^2	25.1 (22.6-28.5)
Baseline activity level (Marx activity score), median (IQR)	11 (4-16)
Previous surgical data	
Time since last ACL reconstruction, median (IQR), y	3.4 (1.4-8.3)
Revision number	
1	1055 (88)
2	125 (10)
≥3	25 (2)
Surgeon's opinion of failure	
Traumatic	405 (34)
Technical	265 (22)
Biological/other	135 (11)
Combination	398 (33)
Cause of technical failure (surgeon's opinion)	
Tunnel malpositioning	532 (45)
Other	76 (6)
Combination	114 (10)
None	452 (39)
Surgeon's revision of his/her own failure	
No	859 (72)
Yes	341 (28)
Prior surgical technique	
1-incision	975 (81)
2-incision	203 (17)
Open arthrotomy	22 (2)
Technique of prior femoral tunnel	
Single tunnel	1167 (98)
Double tunnel	18 (2)
Previous femoral fixation	
Interference screw	721 (60)
Endobutton	205 (17)
Cross pin	149 (12)
Other	101 (8)
Combination	25 (2)
Prior femoral tunnel aperture position[b]	
Ideal	386 (33)
Ideal (both position and size) but enlarged tunnels	28 (2)
Compromised (position)	689 (58)
Compromised (size)	20 (2)
Compromised (both position and size)	60 (5)
Prior tibial fixation	
Interference screw	857 (71)
Other	241 (20)
Combination	101 (8)
Prior tibial tunnel aperture position[b]	
Ideal	721 (60)
Ideal (both position and size) but enlarged tunnels	72 (6)
Compromised (position)	338 (28)
Compromised (size)	35 (3)
Compromised (both position and size)	27 (2)
Current surgical data	
Surgical exposure/technique	
Anteromedial portal	556 (46)
Transtibial	426 (36)
2-incision	211 (18)
Open arthrotomy	6 (1)
Notchplasty	
No	277 (23)
Yes	927 (77)

(continued)

TABLE 1
(continued)

	Value
Femoral tunnel aperture position	
Optimum position	324 (27)
Same tunnel, but compromised position	23 (2)
Blended new/old tunnel	220 (18)
Entirely new tunnel	590 (49)
Added second tunnel	45 (4)
Femoral tunnel bone graft	
None	1082 (90)
Staged (prior)	87 (7)
Yes (current)	32 (3)
Femoral fixation	
Interference screw: metal	522 (43)
Interference screw: bioabsorbable	154 (13)
Suture and button/endobutton	251 (21)
Cross pin	144 (12)
Other	55 (5)
Combination	76 (6)
Tibial tunnel aperture position	
Optimum position	692 (58)
Same tunnel, but compromised position	23 (2)
Blended new tunnel	248 (21)
Entirely new tunnel	199 (17)
Added second tunnel	41 (3)
Tibial tunnel bone graft	
None	1076 (89)
Staged (prior)	93 (8)
Yes (current)	34 (3)
Tibial fixation	
Interference screw: metal	386 (32)
Interference screw: bioabsorbable	297 (25)
Interference screw and suture	41 (3)
Intrafix	107 (9)
Other	124 (10)
Combination	247 (21)
Graft	
Autograft: BTB	336 (28)
Autograft: soft tissue	244 (20)
Allograft: BTB	287 (24)
Allograft: soft tissue	298 (25)
Other (ie, autograft and allograft)	39 (3)
Biological enhancement	
No	1103 (92)
Yes	97 (8)
Knee position at the time of graft fixation, median (IQR), deg of flexion	10 (0-20)
Knee position at the time of graft fixation, median (IQR), deg of hyperextension	0 (0-0)
Surgeon's experience, median (IQR), y	13 (8-18)

[a]Values are expressed as n (%) of non-missing values, unless otherwise specified. ACL, anterior cruciate ligament; BTB, bone–patellar tendon–bone; IQR, interquartile range.

[b]All tunnel determinations for position and size are individual surgeons' determinations.

subscales, IKDC, and all WOMAC subscales ($P < .001$) (Table 2). Lower baseline activity levels (Marx activity scores) predicted worse 2-year Marx activity scores; KOOS pain, ADL, sports/recreation, and QOL subscores; and IKDC, WOMAC pain, and ADL subscores ($P < .01$). A higher BMI predicted worse outcomes for all the KOOS subscales, IKDC, and WOMAC pain and ADL subscales ($P \leq .01$). Female sex predicted worse outcomes for the Marx activity rating scale, KOOS ADL subscale, IKDC,

TABLE 2
Outcomes for Variables in the Model[a]

	Reference Value	Worse Outcome	Marx	KOOS					IKDC	WOMAC		
				Symptoms	Pain	ADL	Sports/ Recreation	QOL		Stiffness	Pain	ADL
Patient demographics												
Age		Older age	1.04 (1.02-1.05); *P* < .001									
Sex	Male	Female	1.93 (1.50-2.49); *P* < .001			1.30 (1.01-1.66); *P* = .041			1.67 (1.30-2.13); *P* < .001		1.36 (1.05-1.76); *P* = .018	1.30 (1.01-1.66); *P* = .041
BMI		Higher BMI		1.04 (1.01-1.08); *P* = .014	1.04 (1.01-1.08); *P* = .008	1.06 (1.03-1.10); *P* < .001	1.04 (1.01-1.08); *P* = .003	1.04 (1.01-1.08); *P* = .012	1.06 (1.03-1.09); *P* < .001		1.05 (1.02-1.09); *P* = .001	1.06 (1.03-1.10); *P* < .001
Baseline activity level (Marx activity score)		Lower activity level	1.15 (1.13-1.18); *P* < .001		1.03 (1.01-1.06); *P* = .004	1.03 (1.01-1.06); *P* = .006	1.05 (1.02-1.07); *P* < .001	1.05 (1.02-1.07); *P* < .001	1.07 (1.04-1.09); *P* < .001		1.03 (1.01-1.06); *P* = .008	1.03 (1.01-1.06); *P* = .006
Baseline outcome scores		Lower baseline scores	1.15 (1.13-1.18); *P* < .001	1.05 (1.04-1.05); *P* < .001	1.05 (1.04-1.06); *P* < .001	1.06 (1.05-1.06); *P* < .001	1.03 (1.02-1.03); *P* < .001	1.03 (1.02-1.04); *P* < .001	1.05 (1.04-1.05); *P* < .001	1.04 (1.03-1.05); *P* < .001	1.05 (1.04-1.06); *P* < .001	1.06 (1.05-1.06); *P* < .001
Surgical data												
Time since last ACL reconstruction		Shorter time since last ACL reconstruction		1.05 (1.02-1.08); *P* < .001	1.06 (1.03-1.09); *P* < .001	1.07 (1.04-1.10); *P* < .001	1.06 (1.03-1.09); *P* < .001	1.05 (1.02-1.08); *P* < .001	1.05 (1.02-1.08); *P* = .002	1.07 (1.03-1.10); *P* < .001	1.07 (1.03-1.10); *P* < .001	1.07 (1.04-1.10); *P* < .001
Revision number	1	2						1.64 (1.10-2.44); *P* = .014				
Surgeon's experience		Fewer years of experience									1.03 (1.01-1.05); *P* = .007	
Surgeon's revision of his/her own failure		Not surgeon's own failure	1.52 (1.08-2.14); *P* = .015									
Surgical approach and tunnel position												
Prior												
Surgical approach/ exposure	1-incision	Open arthrotomy			2.38 (1.03-5.56); *P* = .042		3.13 (1.25-7.69); *P* = .015	4.35 (1.85-10.00); *P* = .001	2.43 (1.05-5.88); *P* = .037			
Femoral tunnel technique	Single tunnel	Double tunnel						3.13 (1.14-8.33); *P* = .027				
Femoral tunnel aperture position												
Tibial tunnel aperture position	Ideal (both position and size) but enlarged tunnels	Ideal			2.03 (1.20-3.42); *P* = .008	1.88 (1.11-3.19); *P* = .019	1.79 (1.06-3.02); *P* = .030	2.06 (1.21-3.52); *P* = .008	1.19 (1.14-3.22); *P* = .014	2.68 (1.53-4.70); *P* = .001	2.13 (1.22-3.70); *P* = .008	1.88 (1.11-3.19); *P* = .019
Current												
Surgical approach/ exposure	Anteromedial portal	2-incision	1.54 (1.04-2.22); *P* = .029	1.52 (1.04-2.22); *P* = .028								
Femoral tunnel aperture position	Entirely new tunnel	Optimum position						1.79 (1.08-2.94); *P* = .025				
Tibial tunnel aperture position	Optimum position	Adding second tunnel				3.45 (1.16-10.00); *P* = .026						3.45 (1.16-10.00); *P* = .026
Notchplasty	No	Yes				1.41 (1.03-1.93); *P* = .034		1.40 (1.03-1.89); *P* = .031	1.47 (1.08-1.99); *P* = .013	1.49 (1.08-2.05); *P* = .015		1.41 (1.03-1.93); *P* = .034
Knee position at the time of graft fixation (deg of flexion)												
Fixation												
Current femoral fixation	Interference screw: metal	Interference screw: bioabsorbable		1.96 (1.18-3.33); *P* = .010	1.70 (1.00-2.86); *P* = .051							
	Interference screw: metal	Cross pin								1.75 (1.02-3.03); *P* = .041		
	Interference screw: metal	Combination						1.92 (1.11-3.33); *P* = .019				
Current tibial fixation	Interference screw: metal	Combination							1.67 (1.10-2.50); *P* = .017	1.72 (1.12-2.63); *P* = .013		

(continued)

TABLE 2
(continued)

	Reference Value	Worse Outcome	Marx	KOOS Symptoms	KOOS Pain	KOOS ADL	KOOS Sports/ Recreation	KOOS QOL	IKDC	WOMAC Stiffness	WOMAC Pain	WOMAC ADL
Biology												
Femoral tunnel bone graft	None	Yes (current)	2.04 (1.00-4.17); *P* = .048									
Tibial tunnel bone graft	Yes (current)	None			1.95 (1.01-3.75); *P* = .046						3.31 (1.47-7.44); *P* = .004	
Biological enhancement	None	Yes	1.79 (1.08-2.94); *P* = .025									

[a]Values are expressed as odds ratio (95% CI) unless otherwise specified. An empty cell indicates that the particular knee outcome in the top (first) row was not significantly affected by the listed variable in the left (first) column. ACL, anterior cruciate ligament; ADL, activities of daily living; BMI, body mass index; IKDC, International Knee Documentation Committee; KOOS, Knee Injury and Osteoarthritis Outcome Score; QOL, quality of life; WOMAC, Western Ontario and McMaster Universities Osteoarthritis Index.

and WOMAC pain and ADL subscales. Older age predicted lower 2-year Marx activity scores ($P < .001$). A shorter time since the last ACL reconstruction predicted worse outcomes for all the KOOS subscales and all WOMAC subscales in addition to the IKDC ($P \leq .002$). A second revision or higher predicted worse outcomes for the KOOS QOL subscale ($P = .014$). If a patient underwent revision that was not a result of the surgeon's own failure, it predicted a worse Marx activity score at 2 years ($P = .015$).

DISCUSSION

The goal of this study was to determine if surgeon-modifiable factors could be identified that were associated with improved outcomes. While there are a few variables that can be influenced by the surgeon, many are beyond the control or do not affect outcomes enough to drive technique changes. Tunnel position, fixation, bone grafting, and biological agent usage are at least somewhat controlled by the surgeon and are associated with outcomes.

The tunnel position has a variety of presentations in the revision setting, and how to drill a new tunnel may be controllable for the surgeon. The pre-existing tunnel may be appropriately placed and utilized again, it may be so poorly positioned that an entirely new tunnel is drilled, or it may be a combination that, when drilled again, results in a blended tunnel that may have a wider aperture. It was feared that a blended tunnel with a wide aperture might result in worse outcomes or higher failure rates. Interestingly, a blended tunnel for the femur and tibia did not affect outcomes. However, utilizing a previous tunnel did not result in outcomes as good as those obtained by a completely new tunnel. It may be surmised that, at times, using a previous tunnel was at some level a compromise of position by not wanting a blended tunnel. Additionally, revision graft healing within a previously utilized tunnel may affect outcomes at a level that this current study is unable to detect or measure. There may be biological factors that we are not yet able to detect that compromise outcomes, despite correctly drilled tunnels and appropriately placed grafts. Additionally, some factors that predict outcomes in this study may not actually be causative but are surrogates for factors that we have not yet identified with our research.

Transtibial drilling did not predict outcomes, despite some surgeons' belief that anteromedial portal drilling allows the independent and improved ability to localize the femoral tunnel. Previous clinical studies have corroborated this finding that anteromedial portal drilling, while theoretically an improvement, has not necessarily been verified in clinical findings in the primary ACL reconstruction setting.[19,21] Two-incision femoral tunnel drilling versus anteromedial portal drilling affected outcomes as measured by the KOOS symptoms subscale ($P = .028$; OR, 1.52). A previous study has not corroborated this finding in which both methods resulted in similar outcomes.[13]

Graft fixation surprisingly affected outcomes in this revision setting. Fixation has rarely been demonstrated to make a clinical difference in the primary setting, where most fixation methods appear adequate for both soft tissue autografts and allografts and patellar tendon autografts and allografts.[4,7,17] In the current study, metal femoral fixation resulted in significantly improved KOOS pain, symptoms, and QOL subscores. Additionally, the use of a metal screw versus a combination of fixation devices for the tibia improved IKDC scores and WOMAC stiffness subscores. It is not possible to determine the exact pathophysiological reason that this predicts outcomes, but bone quality is often worse in the revision setting because of previous tunnels, even if not enlarged, and the use of metal fixation may overcome some of these challenges. Additionally, metal as an inert implant may offer less reactivity than bioabsorbable material in the revision ACL reconstruction setting.

Bone grafting, either 1- or 2-staged, of dilated tunnels can be challenging for patients, resulting in additional surgery and time to ultimate revision if staged. Thus, it is important to determine if this affects outcomes. For dilated tibial tunnels requiring bone grafting, it significantly improves patient outcomes as measured by the KOOS pain and WOMAC pain subscales. Unfortunately, femoral tunnel bone grafting predicted a worse Marx activity score at 2 years. This represents one of those findings that are challenging to incorporate in practice. Bone grafting a femoral tunnel that is too dilated should not be avoided to try to improve 2-year Marx activity scores. Also, the utilization of biological agents to enhance surgical results was not shown to improve outcomes and in fact demonstrated worse 2-year Marx activity scores.

Other factors that were noted to affect outcomes, but may not be modifiable, included notchplasty, which resulted in worse KOOS ADL and QOL subscores, IKDC scores, and WOMAC stiffness and ADL subscores. If notchplasty is definitely needed, as determined by the surgeon, then there remains little choice in performing this step in reconstruction. Typically, in the revision setting, this represents notch overgrowth and may be a surrogate indicator of degenerative processes occurring throughout the joint. Within the limits of our study, it remains uncertain why notchplasty would be associated with worse outcomes, but our analysis controlled for a variety of variables including chondral damage, and thus, it remains an independent predictor. Whether notchplasty was performed or not is all that was recorded, so the size or amount of notchplasty may matter, but that is beyond the scope of our study. The presence of 2 femoral tunnels from previous surgery was associated with a worse outcome but is not a surgically modifiable variable. Previous arthrotomy resulted in worse outcomes but is also not able to be modified.

The strengths of the study include the prospective data collection of validated patient-reported outcome measures with the largest, prospective revision ACL reconstruction cohort assembled to date. This allowed a multivariable analysis of a high number of factors. Weaknesses include no on-site follow-up; surgeons' variations in tunnel drilling as to blended versus previous tunnel usage; and inability to control indications for bone grafting, tunnel placement, and fixation choice by surgeons.

CONCLUSION

A variety of surgical variables are represented in the revision ACL reconstruction setting. Some are modifiable, but unfortunately, many remain beyond the individual surgeon's control. The strongest predictor for revision surgery that is controlled by the surgeon was femoral fixation in which a metal screw improved outcomes. Additional factors that less strongly affected outcomes included drilling a new femoral tunnel versus utilizing a previous tunnel and bone grafting the tibia when indicated. The surgical approach for femoral drilling was not a large factor, with no advantage of the anteromedial versus transtibial technique, but there was some improvement of the anteromedial over the 2-incision technique. Surgeons must balance a variety of these factors on revision ACL reconstruction outcomes along with graft choice, meniscal and articular cartilage findings, and surgical management to optimize outcomes in this challenging clinical setting.

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REFERENCES

1. Ahlden M, Samuelsson K, Sernert N, Forssblad M, Karlsson J, Kartus J. The Swedish National Anterior Cruciate Ligament Register: a report on baseline variables and outcomes of surgery for almost 18,000 patients. *Am J Sports Med*. 2012;40(10):2230-2235.
2. Ahn JH, Lee YS, Ha HC. Comparison of revision surgery with primary anterior cruciate ligament reconstruction and outcome of revision surgery between different graft materials. *Am J Sports Med*. 2008;36(10):1889-1895.
3. Andriolo L, Filardo G, Kon E, et al. Revision anterior cruciate ligament reconstruction: clinical outcome and evidence for return to sport. *Knee Surg Sports Traumatol Arthrosc*. 2015;23(10):2825-2845.
4. Bjorkman P, Sandelin J, Harilainen A. A randomized prospective controlled study with 5-year follow-up of cross-pin femoral fixation versus metal interference screw fixation in anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2015;23(8):2353-2359.
5. Bottoni CR, Smith EL, Shaha J, et al. Autograft versus allograft anterior cruciate ligament reconstruction: a prospective, randomized clinical study with a minimum 10-year follow-up. *Am J Sports Med*. 2015;43(10):2501-2509.
6. Brophy RH, Haas AK, Huston LJ, Nwosu SK, MARS Group, Wright RW. Association of meniscal status, lower extremity alignment, and body mass index with chondrosis at revision anterior cruciate ligament reconstruction. *Am J Sports Med*. 2015;43(7):1616-1622.
7. De Wall M, Scholes CJ, Patel S, Coolican MR, Parker DA. Tibial fixation in anterior cruciate ligament reconstruction: a prospective randomized study comparing metal interference screw and staples with a centrally placed polyethylene screw and sheath. *Am J Sports Med*. 2011;39(9):1858-1864.
8. Filbay SR, Ackerman IN, Russell TG, Macri EM, Crossley KM. Health-related quality of life after anterior cruciate ligament reconstruction: a systematic review. *Am J Sports Med*. 2014;42(5):1247-1255.
9. George MS, Dunn WR, Spindler KP. Current concepts review: revision anterior cruciate ligament reconstruction. *Am J Sports Med*. 2006;34(12):2026-2037.
10. Griffith TB, Allen BJ, Levy BA, Stuart MJ, Dahm DL. Outcomes of repeat revision anterior cruciate ligament reconstruction. *Am J Sports Med*. 2013;41(6):1296-1301.
11. Hettrich CM, Dunn WR, Reinke EK, MARS Group, Spindler KP. The rate of subsequent surgery and predictors after anterior cruciate ligament reconstruction: two- and 6-year follow-up results from a multicenter cohort. *Am J Sports Med*. 2013;41(7):1534-1540.
12. Kvist J, Kartus J, Karlsson J, Forssblad M. Results from the Swedish National Anterior Cruciate Ligament Register. *Arthroscopy*. 2014; 30(7):803-810.
13. Lansdown DA, Allen C, Zaid M, et al. A comprehensive in vivo kinematic, quantitative MRI and functional evaluation following ACL reconstruction: a comparison between mini-two incision and anteromedial portal femoral tunnel drilling. *Knee*. 2015;22(6):547-553.
14. MARS Group. Effect of graft choice on the outcome of revision anterior cruciate ligament reconstruction in the Multicenter ACL Revision Study (MARS) cohort. *Am J Sports Med*. 2014;42(10):2301-2310.
15. MARS Group. Factors influencing graft choice in revision anterior cruciate ligament reconstruction in the MARS group. *J Knee Surg*. 2016;29(6):458-463.
16. MARS Group, Wright RW, Huston LJ, et al. Descriptive epidemiology of the Multicenter ACL Revision (MARS) cohort. *Am J Sports Med*. 2010;38(10):1979-1986.
17. Mascarenhas R, Saltzman BM, Sayegh ET, et al. Bioabsorbable versus metallic interference screws in anterior cruciate ligament

reconstruction: a systematic review of overlapping meta-analyses. *Arthroscopy*. 2015;31(3):561-568.
18. Matava MJ, Arciero RA, Baumgarten KM, et al. Multirater agreement of the causes of anterior cruciate ligament reconstruction failure: a radiographic and video analysis of the MARS cohort. *Am J Sports Med*. 2015;43(2):310-319.
19. Noh JH, Roh YH, Yang BG, Yi SR, Lee SY. Femoral tunnel position on conventional magnetic resonance imaging after anterior cruciate ligament reconstruction in young men: transtibial technique versus anteromedial portal technique. *Arthroscopy*. 2013;29(5):882-890.
20. Salmon LJ, Pinczewski LA, Russell VJ, Refshauge K. Revision anterior cruciate ligament reconstruction with hamstring tendon autograft: 5- to 9-year follow-up. *Am J Sports Med*. 2006;34(10):1604-1614.
21. Wang H, Fleischli JE, Zheng NN. Transtibial versus anteromedial portal technique in single-bundle anterior cruciate ligament reconstruction: outcomes of knee joint kinematics during walking. *Am J Sports Med*. 2013;41(8):1847-1856.
22. Wegrzyn J, Chouteau J, Philippot R, Fessy MH, Moyen B. Repeat revision of anterior cruciate ligament reconstruction: a retrospective review of management and outcome of 10 patients with an average 3-year follow-up. *Am J Sports Med*. 2009;37(4):776-785.
23. Wright R, Spindler K, Huston L, et al. Revision ACL reconstruction outcomes: MOON cohort. *J Knee Surg*. 2011;24(4):289-294.
24. Wright RW. Osteoarthritis classification scales: interobserver reliability and arthroscopic correlation. *J Bone Joint Surg Am*. 2014;96(14):1145-1151.
25. Wright RW, Dunn WR, Amendola A, et al. Anterior cruciate ligament revision reconstruction: two-year results from the MOON cohort. *J Knee Surg*. 2007;20(4):308-311.
26. Wright RW, Gill CS, Chen L, et al. Outcome of revision anterior cruciate ligament reconstruction: a systematic review. *J Bone Joint Surg Am*. 2012;94(6):531-536.
27. Wright RW, Huston LJ, Spindler KP, et al. Descriptive epidemiology of the Multicenter ACL Revision Study (MARS) cohort. *Am J Sports Med*. 2010;38(10):1979-1986.