Title

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Descriptive Characteristics and Outcomes of Patients Undergoing Revision Anterior Cruciate Ligament Reconstruction with and without Tunnel Bone Grafting

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Abstract

Background: Lytic or malpositioned tunnels may require bone grafting during revision anterior cruciate ligament (ACL) reconstruction surgery. Patient characteristics, and impact of grafting on outcomes following revision ACL reconstruction (rACLR) are not well described.

Hypothesis/Purpose: Describe preoperative characteristics, intraoperative findings, and 2-year outcomes for rACLR patients undergoing bone grafting procedures compared to rACLR patients without grafting.

Study Design: Cohort Study, Level of Evidence 3

Methods: 1234 patients who underwent rACLR were prospectively enrolled between 2006 and 2011. Baseline revision and 2-year demographics, surgical technique, pathology, treatment, and patient-reported outcome instruments (IKDC, KOOS, WOMAC, Marx activity score) were collected, as well as subsequent surgery information, if applicable. Group characteristics were compared using chi-squared and ANOVA statistical analyses.

Results: 159 subjects (13%) underwent tunnel grafting: 64 (5%) underwent single-stage and 95 (8%) underwent two-stage grafting. Grafting was isolated to the femur in 31 (2.5%) subjects, tibia in 40 (3%), and combined in 88 (7%). Baseline KOOS quality-of-life (QOL) and Marx activity scores were significantly lower in the two-stage compared to the no bone grafting group ($p<0.001$). Patients who required 2-stage grafting had more prior ACL reconstructions ($p<0.001$) and were less likely to have received BTB or soft tissue autograft at primary ACLR procedure ($p\leq0.02$) compared to the no bone grafting group. For current rACLR, patients undergoing either 1 or 2-stage bone grafting were more likely to receive BTB allograft ($p\leq0.008$) and less likely to receive a soft tissue autograft ($p\leq0.003$) compared to the no bone grafting group. Two-year follow-up on 1052 (85%) subjects found inferior outcomes in the 2-stage bone graft group (IDKC, KOOS QOL, sports recreation, and Marx activity) compared to no bone grafting ($p\leq0.01$). The single-stage bone graft group did not significantly differ compared to the no bone grafting group.

Conclusion: Tunnel bone grafting was performed in 13% of our rACLR cohort, with 8% undergoing 2-staged surgery. Patients treated with 2-stage grafting had inferior baseline and 2-year patient-reported outcomes and activity levels compared to patients not undergoing bone grafting.

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Patients treated with single-stage grafting had similar baseline and 2-year patient-reported outcomes and activity levels compared to patients not undergoing bone grafting.

Social Media Statement:

Large multi-center study finds that two stage bone grafting may lead to inferior 2-year outcomes in revision ACL surgery compared to patients who don't require grafting. #ACL #knee #surgery #MARS #research #revision #bone grafting #tunnels

Keywords

revision anterior cruciate ligament reconstruction; tunnel lysis; bone graft; outcomes

Introduction

Revision anterior cruciate ligament (ACL) reconstruction (rACLR) is a technically demanding procedure with many challenges and pitfalls. Multiple studies have shown worse patient-reported and functional outcomes following rACLR compared to those undergoing primary ACL reconstruction.[1,9,11,24,25] Such outcomes led to the development of the Multicenter ACL Revision Study (MARS) Group to perform a prospective cohort study of patients undergoing rACLR in order to best determine predictors of clinical outcome.[16] While the poor outcomes associated with rACLR may be due to a number of clinical and surgical factors, tunnel malposition and widening are a particular concern, sometimes necessitating bone grafting either in a single (concurrent with the rACLR) or two-staged fashion.[15,16]

Tunnel malposition has been well documented as a primary cause of failure following primary ACLR.[17] In a subset analysis of the MARS database looking at 460 rACLRs, operating surgeons described the cause of failure to be technical in 60% of cases, with 48% attributed to femoral tunnel malposition as the primary cause of failure.[17] The femoral tunnel was judged to be the sole cause of failure in 25% of cases; making femoral tunnel position the most common cause of failure in this study.[17] While the underlying cause of tunnel widening may be a result of graft selection (allograft versus autograft, soft tissue versus bone block), or fixation type (usage of bioscrew or endobuttons), its significance is not completely understood.[29] It however complicates tunnel placement in the setting of rACLR. It is believed that malpositioned tunnels can contribute to widening due to increases in mechanical forces at the tunnel aperture. [10,12] Numerous studies have investigated the cause and pattern of tunnel widening, however it has not shown to significantly affect outcome following primary ACLR.[8,20,23]

Tunnel widening has been described to occur most rapidly in the first year following ACLR, and is more commonly seen with soft tissue grafts and grafts undergoing suspensory fixation.[2,12–14,22] In their 7-year follow-up study, DeFroda et al found that 45 patients with hamstring autografts experienced increasing widening up to 7 years post-operatively, with the most significant widening occurring in post-operative year 1.[5] This is one of the first studies which showed the propensity for widening to continue to occur at intermediate to long-term follow-up after primary ACLR, demonstrating that widening is an evolving

problem with regards to tunnel bone quality and quantity. Widening is particularly important to consider in the rACLR setting, because bone integrity and quality are essential to adequate fixation and graft healing.

When performing rACLR, bone grafting of tunnels is typically indicated for either misplaced tunnels or significant tunnel widening (typically >12 mm)[27], at the discretion of the operating surgeon. This can be a complex decision, but is often indicated if the surgeon believes new tunnel position or fixation will be compromised by poor bone quality or quantity. Despite some agreement on the indications for grafting,[4,27] the effect of bone grafting on patient outcome is not well described. The purpose of this study was to utilize the MARS rACLR cohort to describe preoperative characteristics, intraoperative findings, and 2-year outcomes for rACLR patients undergoing tunnel bone grafting procedures. We hypothesized that those patients undergoing bone grafting (single/concurrent or 2-staged) would be associated with inferior baseline and 2-year post-operative patient-reported outcomes and activity levels compared to a group of rACLR patients not undergoing bone grafting. Secondarily, we hypothesized that within the bone graft cohort, those who required 2-stage bone grafting would have inferior baseline and 2-year post-operative patient-reported outcomes and activity levels compared to patients undergoing single (or current) bone grafting at the time of rACLR. By better understanding patient reported outcomes in rACLR with and without bone grafting, physicians can be better prepared to manage and counsel patients with this complex problem.

Methods

The MARS Group was assembled with the aim of determining what affects outcomes in a rACLR setting and to identify potentially modifiable factors that could improve these outcomes. This collaboration consists of a group of 83 sports medicine fellowship–trained surgeons across 52 sites, with a 54/46% mix of academic and private practitioners. The study design has been previously detailed within prior studies.[15,16] After obtaining approval from each site's institutional review boards, this multicenter consortium began patient enrollment in 2006 and ended in 2011, during which time 1234 patients undergoing rACLR were enrolled in this prospective longitudinal cohort. The study enrolled patients undergoing revision of a previously failed ACLR who agreed to participate, signed an informed consent, and completed a series of patient-reported outcome instruments. Indications for the rACLR included symptomatic patients with functional instability, abnormal laxity testing, or magnetic resonance imaging indicating graft tear/re-tear. Patients with concomitant injuries to the medial and lateral collateral ligaments, posterior cruciate ligament, or posterolateral complex were included. Study exclusion criteria were patients with graft failure secondary to prior intra-articular infection, arthrofibrosis, or complex regional pain syndrome. Surgeon enrollment logs demonstrated that 75% of eligible patients agreed to participate.[16]

Surgeon inclusion criteria included maintenance of an active institutional review board approval, completion of a training session that integrated articular cartilage and meniscal agreement studies, review of the study design and patient inclusion/exclusion criteria, and a review of the surgeon questionnaire. Surgical technique was at the discretion of the treating

surgeon. If an allograft was used, the allograft was obtained from a single allograft supplier (MTF Biologics; Edison, New Jersey, USA).

Data Sources and Measurement

After informed consent was obtained, patients filled out a questionnaire that included questions regarding demographics, sports participation, injury mechanism, comorbidities, and knee injury history, as previously described.[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 post-operatively filled out a questionnaire that included the impression of the etiology (traumatic, technical, and/or biologic) of the previous failure, physical examination findings, surgical technique utilized, the intra-articular findings, and surgical management of meniscal and chondral damage. Bone grafting, if performed (either single or 2-stage), was left up to the surgeon's discretion. Completed data forms were mailed from each participating site to the data coordinating center. Data from the patient and surgeon questionnaires were scanned with Teleform software (OpenText; Waterloo, Ontario, Canada) via optical character recognition, and the scanned data were verified and exported to a master database. A series of custom logical error and quality control checks were periodically performed before data analysis.

Patient Follow-up

Two-year patient follow-up was completed by mail with repeat administration of the same questionnaire as the one completed at baseline. Patients were also contacted by phone and/or email to determine whether any subsequent surgery had occurred to either knee since their initial rACLR. If so, operative reports were obtained, whenever possible, to document pathology and treatment.

Statistical Analysis

To describe our patient sample, we summarized continuous variables as percentiles (i.e., 25th, 50th, and 75th) and categorical variables with frequencies and percentages. Subjects undergoing single or 2-staged bone grafting of ACL tunnels were compared with subjects without tunnel grafting. The association between bone grafting type and other categorical variables were tested using cross tabulations with chi square test of association. For bivariate relationships with chi square values < 0.05, two proportion z-tests were used to determine which proportions were significantly different from one another. Benjamini and Hochberg corrections were applied due to the potential of elevated type-I error associated with multiple comparisons.[3] For continuous variables, group characteristics were compared using chi-squared and ANOVA statistical analyses, with Tukey HSD multiple comparison tests used to determine significant differences between sample means. A p value of <0.05 was set as the significance level. Statistical analysis was performed with open-source R statistical software (v 3.0.3).

Results

Study Population

Of 1234 enrolled patients, a total of 159 subjects (13%) underwent tunnel grafting procedures compared to 1,075 (87%) who did not. Of the patients who underwent a tunnel grafting procedure, 64 (5%) underwent 1-stage (concurrent) bone grafting and 95 (8%) underwent 2-stage bone grafting. Femoral bone grafting was performed on 31 subjects, tibial grafting in 40, and combined grafting in 88 (Table 1). Nearly 90% of the 2-stage bone grafting procedures involved grafting in both the femoral and tibial tunnels, while only 5% of 1-stage bone grafting procedures involved grafting both tunnels. There was no difference in baseline patient demographics (sex, age, BMI, smoking status) between the bone grafted and non-bone grafted revision groups (Table 2).

However, significant differences were noted in baseline KOOS Quality of Life (QOL) and Marx activity level scores, favoring the no bone grafting group compared with the 2-stage bone grafting group; $p < 0.001$ (Table 3). Patients who had single-stage bone grafting were not significantly different than either the 2-stage grafting or no bone grafting groups with regards to their preoperative patient-reported outcome scores.

Surgical History

The surgical history of the bone graft and no bone graft rACLR subjects are detailed in Table 4. The 2-stage bone grafting group was significantly less likely to be undergoing their first revision, compared to the no bone grafting group ($p<0.001$) and the single-stage bone grafting group ($p=0.005$). The 2-stage bone grafting group was also significantly more likely to be undergoing their second or third revision compared to the no bone grafting group ($p<0.001$). Two-staged bone grafting patients were less likely to have received a BTB autograft for their prior ACLR, compared to both the no bone grafting group ($p=0.017$) or the single-stage bone grafting group ($p=0.017$). Similarly, the 2-staged bone grafting patients were more likely to have received an ‘other’ graft, compared to the no bone grafting ($p<0.001$) and single-stage bone grafting ($p=0.002$) groups.

Revision Procedure

The surgical information at the time of the rACLR between the groups are detailed in Table 5.

Graft type used for a patient’s revision procedure was significantly different between the no bone graft group and the two bone grafting groups ($p<0.001$). Specifically, the non-bone grafting group was much less likely to have a BTB allograft, compared to the both the single-stage bone grafting group (21% vs. 44%; $p<0.001$) as well as to the 2-stage bone grafting group (21% vs. 34%; $p=0.008$). Conversely, the non-bone grafting group was much more likely to have a soft tissue autograft, compared to both single-stage (22% vs. 6%; $p=0.003$) and 2-stage (22% vs. 6%; $p=0.001$) bone grafting groups. Femoral fixation was significantly different in the patients requiring bone graft, with both bone-grafting groups more likely to have a metal interference screw (single-stage 70.3% vs 54.2%, $p=0.024$; two-stage 66.3% vs 54.2%, $p=0.036$) and less likely to have a suture/endobutton ($p=0.018$).

Patients undergoing bone grafting were also more likely to have their current revision surgery via a transtibial approach as opposed to other surgical approaches (anteromedial portal, two-incision, arthrotomy) (p=0.024). Femoral bone quality (as reported by the operative surgeon) was more likely to be abnormal in the 2-stage bone grafting group (25.3%), compared to the no bone grafting group (5.8%; p<0.001) and the 1-stage bone grafting group (10.9%; p=0.038). Tibial bone quality was more likely to be abnormal in both the 2-stage (22.1%; p<0.001) and 1-stage (15.6%; p=0.009) bone grafting groups, compared to the no bone grafting group (6.6%). Lastly, the new tunnels were managed differently amongst the bone graft and no bone graft groups at the time of revision (p=0.001; Table 5). Specifically, patients requiring 2-stage bone grafting were significantly more likely to require an entirely new tunnel at the time of revision compared to either the no bone grafting group (p=0.004) or the single-stage bone grafting group (p=0.002; Table 5).

Concomitant Procedures

Medial meniscus pathology at the time of the revision proved to be different between the groups, in that there was more ‘normal’ medial meniscus pathology in the 2-stage bone group compared with the non-bone grafting group (69.5% vs. 53%; p=0.007). For articular cartilage, in the medial femoral compartment, there was significantly more normal/grade 1 classifications in the non-bone grafting group compared with the 2-stage bone grafting group (58% vs. 45%; p=0.044). Similarly, in the medial tibial plateau compartment, there was significantly more normal/grade 1 classifications in the non-bone grafting group compared with the 2-stage bone grafting group (90% vs. 81%; p=0.033). Although not reaching significance (p=0.051), the non-bone grafting group had less grade 2 chondrosis classifications in the medial tibial plateau than both the concomitant (6.8% vs. 14%) and the 2-stage (6.8% vs. 12.6%) bone grafting groups.

Two Year Patient-Reported Outcomes (IKDC, KOOS, WOMAC, and Marx Activity Level)

Clinical outcomes for the two bone grafting groups and no bone graft group are provided in Table 6. Mean IKDC scores were significantly lower in the 2-staged bone grafting group compared to no bone graft (68 vs. 77; p=0.004). There was no significant difference between single-stage bone grafting (72) and no bone grafting (77). Two out of five KOOS subscores were significantly lower in the 2-staged bone graft group compared to no bone graft: sports/recreation (p=0.003), and quality of life (p=0.001). Two-stage grafting was not significantly worse than single-stage grafting with regards to KOOS. WOMAC scores were equivalent between the two grafting groups. Marx activity level was also significantly lower in the 2-staged bone grafting group compared with no bone grafting (p=0.001), but not single-stage bone grafting. (p=0.19).

Incidence of Subsequent Surgery at 2 Years

The rate of subsequent surgery between the groups was also examined (Table 7). In the bone grafting groups, 22 patients (15%) required additional surgery. Sixteen of these were from the 2-staged group versus six in the 1-stage group. Thirteen required arthroscopic surgery for debridement/hardware removal, eight required additional ACLR, and one needed total knee arthroplasty. In the no bone grafting group, 127 (13%) had further intervention. This included 93 arthroscopic interventions, 29 rACLR, and 5 total knee arthroplasties. These

subsequent surgery rates were not significantly different between the bone grafting and no bone grafting groups (p=0.16).

Discussion

This large multicenter cohort study of rACLR patients showed that the need for bone grafting in the revision setting is not uncommon, with 13% of patients requiring either 2-stage (8%) or 1-stage (5%) bone grafting procedures. Most importantly, the present study showed that patients who required 2-staged bone grafting in this study had lower baseline functional scores (KOOS QOL and Marx activity) than patients undergoing revision who did not require grafting. This supported our hypothesis in that patients requiring 2-stage grafting also had lower 2-year post-operative functional outcomes (IKDC, KOOS QOL, sports and activity, and Marx activity level), although this likely exists on a spectrum due to more concomitant intra-articular pathology and the need for more surgeries than patients in other cohorts, as indirectly implied by this cohort's lower baseline functional scores. Contrary to our hypothesis, those patients who underwent a single staged bone grafting procedure did not do significantly worse than rACLR patients who did not require bone graft. Patients who underwent 2-stage bone grafting had more previous rACLRs, a lower percentage of grafts being BTB autograft from their prior ACLR, and a higher percentage of prior medial meniscal repairs and excisions. At the time of rACLR, patients treated via two-stage rACLR had a higher percent of BTB allografts and lower percent of soft tissue autografts used for their current rACLR, as well as a higher incidence of articular cartilage pathology in their medial compartment. Another interesting finding of this study was with regards to the surgical indications and application of bone grafting; almost 90% of the 2-stage bone grafting procedures involved grafting in both the femoral and tibial tunnels, while only 5% of 1-stage bone grafting procedures involved grafting both tunnels, essentially suggesting that surgeons are more likely to perform a 2-stage procedure when both tunnels need to be grafted.

Errant tunnel placement and/or tunnel widening are two situations which require bone grafting in the setting of rACLR. While the effect of tunnel position with regards to ACLR outcomes has been well studied[17,24,26], the literature on the effect of tunnel widening is less clear. A majority of the literature states that tunnel widening does not necessarily correlate with poor functional outcome.[8,20,21,23] In general the clinical cause of widening can vary (biomechanical, attritional bone loss, hardware related, tunnel malposition, infection), and not all widening is created equal, which is likely responsible for the disagreement on its clinical effect in the literature.[29] Struewer et al. reported on 13.5 year follow-up of 73 patients and described tunnel widening as simply a "radiologic phenomenon" which did not progress beyond two years, and did not negatively contribute to clinical outcome or stability.[21] Similarly, Weber et al. performed a 2-year prospective study in which the authors used MRI to follow tibial and femoral tunnel widening over time.[23] The study found progressive tunnel widening up to 24 weeks post-operatively, with no significant widening thereafter. At final follow-up all 18 patients had improvement in their mean Lysholm and IKDC scores regardless of widening, leading the authors to conclude that widening may not influence outcome.[23] It is worth noting that the factors they found to be most associated with increased widening was younger age, male sex, and time from injury to ACLR.[23] While

tunnel widening may not directly correlate with poor outcomes following ACLR, it presents a technical challenge in the revision setting in order to maximize graft fixation.

The true effect of tunnel widening on ACLR patients may be underestimated in the literature due to small sample size and lack of long-term follow-up. While our study did not identify any baseline demographic differences in patients who ultimately required bone grafting during their revision surgery, there were notable differences in their pre-revision function and the characteristics of their primary ACLR. One of the notable findings of this study was that initial graft type seemed to show a significant relationship with the eventual need for bone grafting during rACLR. Patients who required 2-stage bone grafting were less likely to have undergone their primary surgery with a bone-patellar tendon-bone (BTB) autograft than the no bone graft group (p=0.017) or the single-stage bone grafting group (p=0.017). While the literature has not definitively shown a relationship between clinical outcomes and tunnel widening, there are numerous studies which examine the biomechanics of graft choice, and tunnel malalignment with widening.[10,12] One such biomechanical dilemma which soft tissue grafts are subject to has been dubbed the “bungee cord” effect. In this mechanism widening occurs as a result of soft tissue graft fixation being at a distance further from the tunnel aperture than grafts utilizing bone blocks, leading to a large force moment during graft cycling causing widening via longitudinal graft motion within the tunnel.[10,12] This could explain a contributing factor to the higher incidence of bone grafting in patients who underwent their index procedure with soft tissue grafts.

Although there are numerous causes of widening including the aforementioned mechanical mechanisms as well as the effects of heat necrosis and local inflammatory response, it is widely agreed upon that one of the main causes of failure following primary ACLR is malpositioning of the tunnels.[24] One of the early publications from the MARS cohort confirmed this, finding that femoral malposition was present in 47.6% of revision cases.[17] The present study confirmed that tunnel malposition on both the femoral and tibial side increased the need for bone grafting. On the femoral side there were significantly more patients with a compromised tunnel (size and position), and on the tibial side significantly fewer patients had “ideal” tunnel position compared to no bone grafting group (Table 5). Poor tunnel positioning can make these tunnels unusable both due to unfavorable position as well an increased amount of widening due to excessive graft-tunnel motion.[7,18,19] Tunnel malposition is often managed during revision surgery by placement of new tunnels, however in the presence of large amounts of bone loss this may not be possible without grafting.[17] Between the two cohorts, the bone graft patients were significantly more likely to require an entirely new tunnel during rACLR than the no bone graft (Table 5).

Two-year outcomes of the 2-staged bone grafting cohort were significantly worse than the single stage grafting and no bone graft groups. These differences were seen in the IKDC, KOOS quality of life and sports/recreation subscales, as well as the Marx activity score, indicating that patients who required rACLR with 2-staged bone graft were less likely to return to highly active lifestyles. These patients also were more likely to have tunnel widening on both the femoral and tibial side. While the literature is limited with regards to patient-reported outcomes following rACLR with bone grafting, current studies show moderate results at best. Diermeier et al. compared patients who underwent tunnel grafting

both with and without subsequent rACLR in staged fashion.[6] In Diermeier et al's study 44 patients underwent staged rACLR with bone graft, while 10 elected to not undergo ACLR following their grafting procedure. Clinical outcomes between the two groups at mean 33 month follow-up were similar with the rACLR group, reporting an IKDC score of 69 +/− 13.4 and the bone graft only group having a mean IKDC of 69.3 +/− 20.[6] Knee laxity measurements were the only difference between the two groups, which was not surprising.[6] These results are relatively similar to those reported in this study, in which the mean IKDC of staged bone graft patients was 68, compared to 77 in the no bone grafting group. This should be recognized by the operative surgeon and discussed with the patient at length to best set expectations pre-operatively. However, this is not to say that all rACLR patients that required staged bone grafting will do poorly, as the upper 75% quartile of patients in our study reported an IKDC with a mean of 82, indicating that approximately one quarter of patients will still have a good to excellent outcome following rACLR.

Interestingly, when comparing patients who underwent 2-staged versus single stage bone grafting, our analysis found that while 2-staged bone grafting patients had significantly lower functional outcomes than the no bone graft cohort, these patient scores were not significantly lower than those undergoing single grafting. This may indicate that other factors could have contributed to the detrimental outcome of the 2-staged bone grafting group compared with the no bone grafting group. However, this may be deceiving, as the KOOS subscores for sports/recreation, as well as QOL did approach significance ($p=0.07$), and likely would reach significance with larger patient cohorts amongst the staged and concurrent grafting groups. This worse performance for 2-staged patients could be attributable to the need for an additional surgery. In addition, there may have been selection bias with the more severe cases of tunnel lysis or malpositioning required grafting to be performed in a staged fashion and the milder cases being managed with a single stage procedure. One weakness of our multicenter study is that treatment was dictated by surgeon preference. Currently there is no agreed upon treatment algorithm for what patients to bone graft, when to use staged versus concurrent technique, which type of bone graft to use (autograft versus allograft), which type of rehabilitation protocol to follow in between grafting and definitive reconstruction, and how long to wait for graft incorporation prior to reconstruction. A recent systematic review of 7 studies including 234 patients found that autograft may incorporate quicker, with 4 of the studies finding an average time of 4.9 months to radiographic integration, with the second surgery occurring at an average of 6.1 months for patients who underwent iliac crest bone grafting, versus 8.7 months for synthetic and allogenic grafts.[15] Our present study did not investigate choice of bone graft or duration between surgeries, but this may have contributed to the diminished outcome in the staged cohort.

This study has several limitations. First, it is entirely possible that tunnel widening is not the sole reason for inferior outcomes amongst our 2-stage bone grafting cohort. Concomitant meniscal and cartilage pathology, need for increased procedures, as well as a host of other factors could have contributed to this. Despite this we do believe that tunnel widening does play a role in the spectrum of rACLR. It is also worth noting that patients who solely had bone grafting and did not go on to eventual rACLR were not included. This could represent a subset of patients who were happy with their outcome despite ACL deficiency,

and would affect the patient reported outcomes if included. The next weakness is the potential lack of agreement between surgeons regarding contributions to failure, as well as the reliance on surgeons at each site to assess the adequacy of initial tunnel placement. This was minimized as much as possible by the required training of all participating surgeons. To further address this potential weakness, past MARS cohort studies have obtained intraobserver and interobserver agreement with regards to radiographic determination of tunnel position.[15,16] This study required all radiographs to be read by 2 of 3 primary authors to help standardize measurements amongst the surgeons included in the study. Consistently high intraclass correlation coefficients (ICCs) were demonstrated among the three readers for most measurements, with more than 50% higher than 0.7. Intraobserver agreement obtained more than 4 weeks following the initial measurements demonstrated similar results with 36 of 42 measured ICCs more than 0.7.[15] Also there was no determination of the amount of tunnel widening for the two patient cohorts, and the reason for bone grafting (malposition, widening, both) was not recorded. Future radiographic studies should investigate degree of widening within the MARS cohort and determine the effects on clinical outcome in rACLR. Also, the MARS surgeon form just had 4 questions related to bone grafting – 2 for the femoral tunnel and 2 related to the tibial tunnel, without the ability to give more specifics on indications or decision making for bone grafting, type of bone graft used, addition of a biologic, etc; this may have limited data collection on this complex topic. Additionally, because this was a multicenter study consisting of 83 surgeons at 52 sites, indications for concurrent versus staged bone grafting could have differed based on surgeon preference and experience. Of note there was no standardization of the indications for bone grafting, the type of bone graft material used, the indication for concurrent versus staged grafting, or the documentation of graft consolidation prior to definitive rACLR (i.e., CT or plain x-ray). Similarly, graft selection and fixation methods may have varied based on surgeon preference and could have had a potential influence on clinical outcome. It is also possible that worse outcomes in the staged bone grafting cohorts could be further confounded by the need for further surgeries as well as subsequent bone loss due to the need for increased procedures. Also, there was no way to control for differences in rehabilitation, compliance with rehabilitation, or patient response to therapy. Lastly, due to the broad, multicenter scope of this project it was not possible to have a robust amount of objective data available for review with regards to overall ligamentous stability, strength, x-ray, and MRI evaluation. However, despite the limitations of this study, this is the largest study to examine the two-year outcomes of a prospectively collected patient cohort of patients undergoing rACLR with and without the need for bone grafting and adds to the literature on this complicated topic to help aid sports medicine physicians and their patients.

Conclusion

Tunnel bone grafting was performed in 13% of our rACLR cohort, with 8% undergoing 2-staged surgery. Patients treated with 2-stage grafting had inferior baseline and 2-year patient-reported outcomes and activity levels compared to patients not undergoing bone grafting. Patients treated with single-stage grafting had similar baseline and 2-year patient-reported outcomes and activity levels compared to patients not undergoing bone grafting.

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References

1. Battaglia MJ, Cordasco FA, Hannafin JA, et al. Results of Revision Anterior Cruciate Ligament Surgery. Am J Sports Med. 2007;35(12):2057–2066. doi:10.1177/0363546507307391. [PubMed: 17932401]
2. Baumfeld JA, Diduch DR, Rubino LJ, et al. Tunnel widening following anterior cruciate ligament reconstruction using hamstring autograft: a comparison between double cross-pin and suspensory graft fixation. Knee Surg Sports Traumatol Arthrosc. 2008;16(12):1108–1113. doi:10.1007/s00167-008-0606-y. [PubMed: 18791702]
3. Benjamini Y, Hochberg Y. Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing. J R Stat Soc Ser B. 1995;57(1):289–300. http://www.jstor.org/stable/2346101.
4. Chahla J, Dean CS, Cram TR, et al. Two-Stage Revision Anterior Cruciate Ligament Reconstruction: Bone Grafting Technique Using an Allograft Bone Matrix. Arthrosc Tech. 2016;5(1):e189–e195. doi:10.1016/j.eats.2015.10.021. [PubMed: 27274452]
5. DeFroda SF, Karamchedu NP, Owens BD, et al. Tibial tunnel widening following anterior cruciate ligament reconstruction: A retrospective seven-year study evaluating the effects of initial graft tensioning and graft selection. Knee. 2018;25(6):1107–1114. doi:10.1016/j.knee.2018.08.003. [PubMed: 30414786]
6. Diermeier T, Herbst E, Braun S, et al. Outcomes after bone grafting in patients with and without ACL revision surgery: a retrospective study. BMC Musculoskelet Disord. 2018;19(1):246. doi:10.1186/s12891-018-2174-8. [PubMed: 30031398]
7. Fahey M, Indelicato PA. Bone Tunnel Enlargement After Anterior Cruciate Ligament Replacement. Am J Sports Med. 1994;22(3):410–414. doi:10.1177/036354659402200318. [PubMed: 8037283]
8. Fink C, Zapp M, Benedetto KP, Hackl W, Hoser C, Rieger M. Tibial tunnel enlargement following anterior cruciate ligament reconstruction with patellar tendon autograft. Arthrosc J Arthrosc Relat Surg. 2001;17(2):138–143. doi:10.1053/jars.2001.21509.
9. George MS, Dunn WR, Spindler KP. Current Concepts Review: Revision Anterior Cruciate Ligament Reconstruction. Am J Sports Med. 2006;34(12):2026–2037. doi:10.1177/0363546506295026. [PubMed: 17092921]
10. Höher J, Möller HD, Fu FH. Bone tunnel enlargement after anterior cruciate ligament reconstruction: fact or fiction? Knee Surgery, Sport Traumatol Arthrosc. 1998;6(4):231–240. doi:10.1007/s001670050105.
11. Kamath G V, Redfern JC, Greis PE, Burks RT. Revision Anterior Cruciate Ligament Reconstruction. Am J Sports Med. 2011;39(1):199–217. doi:10.1177/0363546510370929. [PubMed: 20709943]
12. L'Insalata JC, Klatt B, Fu FH, Harner CD. Tunnel expansion following anterior cruciate ligament reconstruction: a comparison of hamstring and patellar tendon autografts. Knee Surg Sports Traumatol Arthrosc. 1997;5(4):234–238. doi:10.1007/s001670050056. [PubMed: 9430573]
13. Lind M, Feller J, Webster KE. Bone Tunnel Widening After Anterior Cruciate Ligament Reconstruction Using EndoButton or EndoButton Continuous Loop. Arthrosc J Arthrosc Relat Surg. 2009;25(11):1275–1280. doi:10.1016/j.arthro.2009.06.003.

14. Lind M, Feller J, Webster KE. Tibial bone tunnel widening is reduced by polylactate/hydroxyapatite interference screws compared to metal screws after ACL reconstruction with hamstring grafts. Knee. 2009;16(6):447–451. doi:10.1016/j.knee.2009.04.003. [PubMed: 19423351]
15. MARS Group M Radiographic findings in revision anterior cruciate ligament reconstructions from the Mars cohort. J Knee Surg. 2013;26(4):239–247. doi:10.1055/s-0032-1329717. [PubMed: 23404491]
16. MARS Group RW, Wright RW, Huston LJ, et al. Descriptive epidemiology of the Multicenter ACL Revision Study (MARS) cohort. Am J Sports Med. 2010;38(10):1979–1986. doi:10.1177/0363546510378645. [PubMed: 20889962]
17. Morgan JA, Dahm D, Levy B, Stuart MJ, MARS Study Group MS. Femoral tunnel malposition in ACL revision reconstruction. J Knee Surg. 2012;25(5):361–368. doi:10.1055/s-0031-1299662. [PubMed: 23150344]
18. Nebelung W, Becker R, Merkel M, Röpke M. Bone tunnel enlargement after anterior cruciate ligament reconstruction with semitendinosus tendon using Endobutton fixation on the femoral side. Arthroscopy. 14(8):810–815. doi:10.1016/s0749-8063(98)70015-5.
19. Otsuka H, Ishibashi Y, Tsuda E, Sasaki K, Toh S. Comparison of Three Techniques of Anterior Cruciate Ligament Reconstruction with Bone-Patellar Tendon-Bone Graft: Differences in Anterior Tibial Translation and Tunnel Enlargement with Each Technique. Am J Sports Med. 2003;31(2):282–288. doi:10.1177/03635465030310022101. [PubMed: 12642266]
20. Rodeo SA, Kawamura S, Kim H-J, Dynybil C, Ying L. Tendon Healing in a Bone Tunnel Differs at the Tunnel Entrance versus the Tunnel Exit. Am J Sports Med. 2006;34(11):1790–1800. doi:10.1177/0363546506290059. [PubMed: 16861579]
21. Struewer J, Efe T, Frangen TM, et al. Prevalence and influence of tibial tunnel widening after isolated anterior cruciate ligament reconstruction using patella-bone-tendon-bone-graft: long-term follow-up. Orthop Rev (Pavia). 2012;4(2):e21. doi:10.4081/or.2012.e21. [PubMed: 22802989]
22. Wang JH, Lee ES, Lee BH. Paradoxical tunnel enlargement after ACL reconstruction with hamstring autografts when using β-TCP containing interference screws for tibial aperture fixation-prospectively comparative study. BMC Musculoskelet Disord. 2017;18(1):398. doi:10.1186/s12891-017-1757-0. [PubMed: 28915914]
23. Weber AE, Delos D, Oltean HN, et al. Tibial and Femoral Tunnel Changes After ACL Reconstruction. Am J Sports Med. 2015;43(5):1147–1156. doi:10.1177/0363546515570461. [PubMed: 25681503]
24. 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. http://www.ncbi.nlm.nih.gov/pubmed/17993075. Accessed October 12, 2019. [PubMed: 17993075]
25. Wright RW, Gill CS, Chen L, et al. Outcome of Revision Anterior Cruciate Ligament Reconstruction: A Systematic Review. J Bone Jt Surgery-American Vol. 2012;94(6):531–536. doi:10.2106/JBJS.K.00733.
26. Wright RW, Huston LJ, Haas AK, et al. Predictors of Patient-Reported Outcomes at 2 Years After Revision Anterior Cruciate Ligament Reconstruction. Am J Sports Med. 2019;47(10):2394–2401. doi:10.1177/0363546519862279. [PubMed: 31318611]
27. Yamaguchi KT, Mosich GM, Jones KJ. Arthroscopic Delivery of Injectable Bone Graft for Staged Revision Anterior Cruciate Ligament Reconstruction. Arthrosc Tech. 2017;6(6):e2223–e2227. doi:10.1016/j.eats.2017.08.025. [PubMed: 29349022]
28. Yates D, Moore, Moore D, McCabe G. The Practice of Statistics (1st Ed.). 1st ed. (WH Freeman, ed.). New York, NY; 1999.
29. Yue L, DeFroda SF, Sullivan K, Garcia D, Owens BD. Mechanisms of Bone Tunnel Enlargement Following Anterior Cruciate Ligament Reconstruction. JBJS Rev. 2020;8(4):e0120. doi:10.2106/jbjs.rvw.19.00120. [PubMed: 32539260]

What is known about the subject:

It is widely accepted that patients undergoing rACLR do worse than those undergoing primary ACL reconstruction for a multitude of reasons. However, there is limited clinical data investigating various cohorts of rACLR patients, including those requiring bone grafting of their tibial and femoral tunnels and those who do not. Additionally, there is no literature to our knowledge investigating differences in outcomes of patients who require staged versus concurrent grafting procedures.

What this study adds to existing knowledge:

This study adds to the literature by being the largest study available to compare cohorts of rACLR patients who did and did not require bone grafting during their management. Future studies should be aimed at identifying the need for grafting (lysis, malposition, both), and the relationship between tunnel lysis and functional outcomes in rACLR patients.

Table 1.

Location of Bone Grafting, stratified by Stage

Location of Bone Grafting	Combined Bone Grafting Groups (n=159)	1-Stage Bone Grafting (n=64)	2-Stage Bone Grafting (n=95)
Femoral Tunnel only	31 (19.5%)	29 (45.3%)	2 (2.1%)
Tibial Tunnel only	40 (25.1%)	32 (50.0%)	8 (8.4%)
Both Femoral and Tibial Tunnels	88 (55.3%)	3 (4.7%)	85 (89.5%)

Key: Variables are listed as frequency (percentage).

Table 2.

Baseline **(pre rACLR)** Patient Demographics

	Overall	Groups			Overall significance test[a]	
	Total (N=1234) n (%)	No Bone Grafting (n=1075) n (%)	1-Stage Bone Grafting (n=64) n (%)	2-Stage Bone Grafting (n=95) n (%)	χ^2 / F	P value
Sex					3.88	0.144
female	518 (42.0%)	443 (41.2%)	26 (40.6%)	49 (51.6%)		
male	716 (58.0%)	632 (58.8%)	38 (59.4%)	46 (48.4%)		
Age (mean ± SD)	27.9 ± 10.0	27.8 ± 10.1	29.1 ± 11.2	27.8 ± 8.6	0.538	0.584
BMI (mean ± SD)	26.1 ± 4.7	26.1 ± 4.6	25.9 ± 4.2	26.7 ± 5.1	0.878	0.416
Smoking Status					6.95	0.139
current	109 (8.8%)	94 (8.8%)	4 (6.3%)	11 (11.6%)		
never	949 (76.9%)	836 (77.7%)	49 (76.6%)	64 (67.4%)		
quit	157 (12.7%)	128 (11.9%)	11 (17.2%)	18 (18.9%)		

Key:

Continuous variables are listed as mean (standard deviation; SD); categorical variables are listed as frequency (percentage). Ns that do not sum to 1234 and percentages that do not sum to 100% reflect missing data.

BMI = body mass index.

[a]Chi-square test of association used to assess significance for categorical variables; ANOVA tests were used for continuous variables.

Table 3.

Baseline (pre rACLR) Patient-Reported Outcome Scores

Median (25%, 75% quartile) Baseline Patient Reported Outcome Scores	Overall (n=1234)	No Bone Grafting (n=1075)	1-Stage Bone Grafting (n=64)	2-Stage Bone Grafting (n=95)	P value
IKDC	52 (38, 63)	52 (39, 64)	51 (39, 60)	48 (34, 59)	0.22
KOOS					
• Symptoms	68 (54, 82)	68 (54, 82)	71 (50, 82)	68 (54, 82)	0.95
• Pain	75 (58, 86)	75 (58, 86)	75 (60, 86)	72 (61, 86)	0.87
• Activities of Daily Living (ADL)	87 (69, 96)	87 (69, 96)	86 (66, 96)	85 (63, 94)	0.66
• Sports/recreation	45 (25, 65)	45 (25, 65)	40 (15, 65)	40 (20, 59)	0.21
• Quality of life (QOL)	31 (19, 44)	31 (19, 44)	31 (13, 45)	25 (13, 38)	**0.001** *1*
WOMAC					
• Stiffness	75 (50, 88)	75 (50, 88)	75 (59, 88)	75 (50, 88)	0.43
• Pain	85 (70, 95)	85 (70, 95)	80 (65, 95)	80 (65, 94)	0.48
• Activities of Daily Living (ADL)	87 (69, 96)	87 (69, 96)	86 (66, 96)	85 (63, 94)	0.64
Marx Activity Level	11 (4, 16)	12 (4, 16)	7 (3, 15)	6 (0, 12)	**<0.001** *2*

Key:

1: ANOVA tests showed a significant difference in this variable between groups (p=0.001). Tukey HSD multiple comparison test showed that the 2-staged bone grafting group was significantly lower than the no bone grafting group (p=0.001). The 2-staged bone grafting group was not significantly lower than the 1-stage bone grafting group (p=0.20).

2: ANOVA tests showed a significant difference in this variable between groups (p<0.001). Tukey HSD multiple comparison test showed that the 2-staged bone grafting group was significantly lower than the no bone grafting group (p<0.001). The 1-stage bone grafting group was not significantly different than the 2-staged bone grafting group (p=0.29) or the no bone grafting group (p=0.07).

Table 4.

Previous Surgical Information on the Cohort

	Overall	Groups			Overall significance test[a]		Pairwise comparisons[b]		
	Total (N=1234) n (%)	No Bone Grafting (n=1075) n (%)	1-Stage Bone Grafting (n=64) n (%)	2-Stage Bone Grafting (n=95) n (%)	χ^2 / F	P value	None vs 1-stage	None vs 2-stage	1-stage vs 2-stage
Median time (in years) since last ACLR	3.3 (1.4, 8.0)	3.0 (1.6, 6.9)	4.7 (1.2, 9.9)	3.3 (1.4, 8.2)	1.26	0.28			
Revision number					80.76	<0.001			
One	1076 (87.3%)	964 (89.8%)	54 (84.4%)	58 (61.1%)			0.519	<0.001	0.005
Two	131 (10.6%)	96 (8.9%)	9 (14.1%)	26 (27.4%)			0.506	<0.001	0.141
3 or more *	26 (2.1%)	14 (1.3%)	1 (1.6%)	11 (11.6%)			--	<0.001	--
Prior Graft Type					39.31	<0.001			
allograft (btb)	136 (11.0%)	118 (11.0%)	6 (9.4%)	12 (12.6%)			0.688	0.688	0.688
allograft (soft tissue)	133 (10.8%)	112 (10.4%)	5 (7.8%)	16 (16.8%)			0.503	0.149	0.149
autograft (btb)	493 (40.0%)	436 (40.6%)	31 (48.4%)	26 (27.4%)			0.215	0.017	0.017
autograft (soft tissue)	326 (26.4%)	295 (27.5%)	17 (26.6%)	14 (14.7%)			0.875	0.021	0.097
other / unknown	145 (11.8%)	113 (10.5%)	5 (7.8%)	27 (28.4%)			0.49	<0.001	0.002
Prior medial meniscal surgery					17.50	0.002			
no	764 (62.0%)	686 (63.9%)	37 (57.8%)	41 (43.2%)			0.328	<0.001	0.105
excision	368 (29.8%)	304 (28.3%)	23 (35.9%)	41 (43.2%)			0.285	0.007	0.363
repair	101 (8.2%)	84 (7.8%)	4 (6.3%)	13 (13.7%)			0.648	0.141	0.205
Prior lateral meniscal surgery					3.37	0.498			
no	978 (79.3%)	854 (79.5%)	54 (84.4%)	70 (73.7%)					
excision	198 (16.1%)	171 (15.9%)	7 (10.9%)	20 (21.1%)					
repair	53 (4.3%)	45 (4.2%)	3 (4.7%)	5 (5.3%)					
Prior surgical technique					0.23	0.892			
1 incision	994 (80.6%)	861 (80.2%)	54 (84.4%)	79 (83.2%)					
2 incision	212 (17.2%)	186 (17.3%)	10 (15.6%)	16 (16.8%)					
arthrotomy *	12 (1.0%)	12 (1.1%)	0 (0.0%)	0 (0.0%)					

	Overall	Groups			Overall significance test[a]		Pairwise comparisons[b]		
	Total (N=1234) n (%)	No Bone Grafting (n=1075) n (%)	1-Stage Bone Grafting (n=64) n (%)	2-Stage Bone Grafting (n=95) n (%)	χ^2 / F	P value	None vs 1-stage	None vs 2-stage	1-stage vs 2-stage
arthrotomy (patellar retinaculum intact) *	10 (0.8%)	10 (0.9%)	0 (0.0%)	0 (0.0%)					
Prior femoral tunnel technique					--	--			
single tunnel	1195 (96.9%)	1038 (96.6%)	63 (98.4%)	94 (98.9%)					
double tunnel *	18 (1.5%)	17 (1.6%)	0 (0.0%)	1 (1.1%)					
Prior femoral fixation					6.46	0.596			
Interference screw (bioabsorbable)	277 (22.5%)	244 (22.7%)	14 (21.9%)	19 (20.0%)					
Interference screw (metal)	450 (36.5%)	381 (35.5%)	29 (45.3%)	40 (42.1%)					
Suture + button/ endobutton	221 (17.9%)	200 (18.6%)	8 (12.5%)	13 (13.7%)					
Cross pin	154 (12.5%)	133 (12.4%)	9 (14.1%)	12 (12.6%)					
Other/combination	130 (10.5%)	115 (10.7%)	4 (6.3%)	11 (11.6%)					
Prior femoral tunnel aperture position					145.28	<0.001			
Ideal	409 (33.2%)	371 (34.5%)	26 (40.6%)	12 (12.6%)			0.382	<0.001	<0.001
Compromised (position)	692 (56.1%)	616 (57.4%)	30 (46.9%)	46 (48.4%)			0.108	0.108	0.799
Compromised (position + size)	60 (4.9%)	29 (2.7%)	5 (7.8%)	26 (27.4%)			0.022	<0.001	0.003
Ideal position + size, but enlarged tunnels *	29 (2.4%)	24 (2.2%)	2 (3.1%)	3 (3.2%)			--	--	--
Compromised (size)	21 (1.7%)	13 (1.2%)	1 (1.6%)	7 (7.4%)			--	<0.001	--
Prior tibial fixation					5.90	0.435			
Interference screw (bioabsorbable)	454 (36.8%)	402 (37.4%)	18 (28.1%)	34 (35.8%)					
Interference screw (metal)	419 (34.0%)	356 (33.1%)	28 (43.8%)	35 (36.8%)					
Combination	118 (9.6%)	100 (9.3%)	5 (7.8%)	13 (13.7%)					
Other	199 (16.1%)	176 (16.4%)	10 (15.6%)	13 (13.7%)					
Intrafix *	37 (3.0%)	34 (3.2%)	3 (4.7%)	0 (0.0%)					
Prior tibial tunnel aperture position					37.31	<0.001			

	Overall	Groups			Overall significance test[a]		Pairwise comparisons[b]		
	Total (N=1234) n (%)	No Bone Grafting (n=1075) n (%)	1-Stage Bone Grafting (n=64) n (%)	2-Stage Bone Grafting (n=95) n (%)	χ^2 / F	P value	None vs 1-stage	None vs 2-stage	1-stage vs 2-stage
Ideal	749 (60.7%)	687 (64.0%)	36 (56.3%)	26 (27.4%)			0.175	<0.001	<0.001
Ideal position + size, but enlarged tunnels	72 (5.8%)	53 (4.9%)	5 (7.8%)	14 (14.7%)			0.320	<0.001	0.269
Compromised (position)	338 (27.4%)	294 (27.4%)	23 (35.9%)	21 (22.1%)			0.229	0.267	0.184
Compromised (size)*	35 (2.8%)	17 (1.6%)	0 (0.0%)	18 (18.9%)			--	<0.001	--
Compromised (position + size)*	27 (2.2%)	12 (1.1%)	0 (0.0%)	15 (15.8%)			--	<0.001	--

Key:

Continuous variables are denoted as median (25%, 75% quartiles)

Non-continuous variables are denoted as N (%)

Ns that do not sum to 1234 and percentages that do not sum to 100% reflect missing data.

ACL = anterior cruciate ligament; BTB = bone-patellar tendon-bone

[a]Chi-square test of association used to assess significance.

[b]Pairwise differences were tested using Z-tests of 2 proportions with Benjamini & Hochberg adjusted p-values. No adjusted pairwise p-values are reported for comparisons using cell size < 5.

*Rows with cell sizes of 0 and those that contributed to >20% of counts <5 are marked with an asterisk and were excluded from the overall significance test due to violation of assumptions).[28] Sensitivity analysis was conducted by leaving these small groups in. Results showed the same pattern of significance.

Table 5.

Surgical Information on the Cohort **at the time of rACLR**

	Overall	Groups			Overall significance test[a]		Pairwise comparisons[b]		
	Total (N=1234) n (%)	No Bone Grafting (n=1075) n (%)	1-Stage Bone Grafting (n=64) n (%)	2-Stage Bone Grafting (n=95) n (%)	χ^2	P value	None vs 1-stage	None vs 2-stage	1-stage vs 2-stage
Current Graft Type					38.39	<0.001			
allograft (BTB)	289 (23.4%)	229 (21.3%)	28 (43.8%)	32 (33.7%)			<0.001	0.008	0.199
allograft (soft tissue)	302 (24.5%)	264 (24.6%)	12 (18.8%)	26 (27.4%)			0.433	0.55	0.433
autograft (BTB)	324 (26.3%)	285 (26.5%)	15 (23.4%)	24 (25.3%)			0.793	0.793	0.793
autograft (soft tissue)	251 (20.4%)	241 (22.4%)	4 (6.3%)	6 (6.3%)			0.003	0.001	0.987
other	66 (5.4%)	54 (5.0%)	5 (7.8%)	7 (7.4%)			0.495	0.495	0.917
Surgical Exposure/ Technique					11.66	0.02			
Anteromedial portal	574 (46.6%)	515 (48.0%)	24 (37.5%)	35 (36.8%)			0.143	0.100	0.933
Transtibial	427 (34.6%)	353 (32.9%)	31 (48.4%)	43 (45.3%)			0.024	0.024	0.694
2 incision	220 (17.8%)	195 (18.2%)	9 (14.1%)	16 (16.8%)			0.731	0.731	0.731
arthrotomy / other *	6 (0.5%)	5 (0.5%)	0 (0.0%)	1 (1.1%)			--	--	--
Notchplasty					1.80	0.406			
no	284 (23.0%)	254 (23.6%)	12 (18.8%)	18 (18.9%)					
yes	948 (76.9%)	819 (76.3%)	52 (81.3%)	77 (81.1%)					
Femoral tunnel aperture position					18.99	0.001			
entirely new tunnel	589 (47.8%)	506 (47.1%)	23 (35.9%)	60 (63.2%)			0.078	0.004	0.002
optimum position	344 (27.9%)	311 (29.0%)	22 (34.4%)	11 (11.6%)			0.362	0.001	0.001
blended new tunnel	223 (18.1%)	190 (17.7%)	16 (25.0%)	17 (17.9%)			0.418	0.970	0.418
same tunnel aperture, but compromised position *	25 (2.0%)	22 (2.0%)	2 (3.1%)	1 (1.1%)			0.563	0.563	0.563
added a 2nd tunnel *	45 (3.6%)	38 (3.5%)	1 (1.6%)	6 (6.3%)			--	0.262	--
over-the-top *	4 (0.3%)	4 (0.4%)	0 (0.0%)	0 (0.0%)			--	--	--
Femoral fixation					18.92	0.004			

	Overall	Groups			Overall significance test[a]		Pairwise comparisons[b]		
	Total (N=1234) n (%)	No Bone Grafting (n=1075) n (%)	1-Stage Bone Grafting (n=64) n (%)	2-Stage Bone Grafting (n=95) n (%)	χ^2	P value	None vs 1-stage	None vs 2-stage	1-stage vs 2-stage
interference screw	690 (56.0%)	582 (54.2%)	45 (70.3%)	63 (66.3%)			0.024	0.036	0.499
suture+button/ endobutton	265 (21.5%)	248 (23.1%)	6 (9.4%)	11 (11.6%)			0.018	0.018	0.683
cross pin	144 (11.7%)	130 (12.1%)	8 (12.5%)	6 (6.3%)			0.893	0.25	0.25
combination	77 (6.2%)	64 (6.0%)	4 (6.3%)	9 (9.5%)			0.902	0.53	0.726
other*	54 (4.4%)	48 (4.5%)	0 (0.0%)	6 (6.3%)			--	0.414	--
Femoral tunnel bone quality					48.31	<0.001			
abnormal	93 (7.5%)	62 (5.8%)	7 (10.9%)	24 (25.3%)			0.095	<0.001	0.038
normal	1135 (92.1%)	1007 (93.8%)	57 (89.1%)	71 (74.7%)			0.095	<0.001	0.038
Tibial tunnel aperture position					41.37	<0.001			
entirely new tunnel	199 (16.1%)	159 (14.8%)	5 (7.8%)	35 (36.8%)			0.121	<0.001	<0.001
optimum position	720 (58.4%)	646 (60.1%)	41 (64.1%)	33 (34.7%)			0.546	<0.001	<0.001
blended new tunnel	248 (20.1%)	212 (19.7%)	17 (26.6%)	19 (20.0%)			0.498	0.958	0.498
added a 2nd tunnel*	41 (3.3%)	33 (3.1%)	0 (0.0%)	8 (8.4%)			--	0.021	--
same tunnel aperture, but compromised position*	23 (1.9%)	22 (2.0%)	1 (1.6%)	0 (0.0%)			--	--	--
Tibial fixation					10.10	0.258			
intrafix	107 (8.7%)	97 (9.0%)	2 (3.1%)	8 (8.4%)					
suture + post or button	65 (5.3%)	57 (5.3%)	3 (4.7%)	5 (5.3%)					
interference screw	707 (57.3%)	616 (57.4%)	43 (67.2%)	48 (50.5%)					
combination	285 (23.1%)	247 (23.0%)	14 (21.9%)	24 (25.3%)					
other	66 (5.4%)	54 (5.0%)	2 (3.1%)	10 (10.5%)					
Tibial tunnel bone quality					32.41	<0.001			
abnormal	102 (8.3%)	71 (6.6%)	10 (15.6%)	21 (22.1%)			0.009	<0.001	0.334
normal	1126 (91.3%)	999 (93.0%)	53 (82.8%)	74 (77.9%)			0.009	<0.001	0.334
Medial meniscus pathology/treatment					14.95	0.021			

	Overall	Groups			Overall significance test[a]		Pairwise comparisons[b]		
	Total (N=1234) n (%)	No Bone Grafting (n=1075) n (%)	1-Stage Bone Grafting (n=64) n (%)	2-Stage Bone Grafting (n=95) n (%)	χ^2	P value	None vs 1-stage	None vs 2-stage	1-stage vs 2-stage
normal	679 (55.1%)	571 (53.2%)	42 (65.6%)	66 (69.5%)			0.078	0.007	0.61
repair	166 (13.5%)	151 (14.1%)	8 (12.5%)	7 (7.4%)			0.727	0.202	0.416
excision	336 (27.3%)	307 (28.6%)	12 (18.8%)	17 (17.9%)			0.133	0.077	0.891
no treatment for tear	29 (2.4%)	26 (2.4%)	2 (3.1%)	1 (1.1%)			--	--	--
other *	23 (1.9%)	19 (1.8%)	0 (0.0%)	4 (4.2%)			--	--	--
Lateral meniscus pathology/treatment					7.33	0.119			
normal	789 (64.0%)	677 (63.0%)	43 (67.2%)	69 (72.6%)					
repair	63 (5.1%)	56 (5.2%)	4 (6.3%)	3 (3.2%)					
excision	316 (25.6%)	287 (26.7%)	15 (23.4%)	14 (14.7%)					
no treatment for tear *	58 (4.7%)	48 (4.5%)	2 (3.1%)	8 (8.4%)					
other *	7 (0.6%)	6 (0.6%)	0 (0.0%)	1 (1.1%)					
LFC articular cartilage pathology					4.34	0.362			
normal/grade 1	880 (71.4%)	765 (71.2%)	45 (70.3%)	70 (73.7%)					
grade 2	189 (15.3%)	169 (15.7%)	6 (9.4%)	14 (14.7%)					
grades 3/4	164 (13.3%)	140 (13.0%)	13 (20.3%)	11 (11.6%)					
MFC articular cartilage pathology					9.73	0.045			
normal/grade 1	699 (56.7%)	624 (58.1%)	32 (50.0%)	43 (45.3%)			0.295	0.044	0.557
grade 2	294 (23.8%)	249 (23.2%)	14 (21.9%)	31 (32.6%)			0.803	0.119	0.21
grades 3/4	238 (19.3%)	199 (18.6%)	18 (28.1%)	21 (22.1%)			0.176	0.398	0.398
LTP articular cartilage pathology					4.66	0.324			
normal/grade 1	1018 (82.6%)	892 (83.1%)	54 (84.4%)	72 (75.8%)					
grade 2	162 (13.1%)	138 (12.8%)	6 (9.4%)	18 (18.9%)					
grades 3/4	53 (4.3%)	44 (4.1%)	4 (6.3%)	5 (5.3%)					
MTP articular cartilage pathology					10.63	0.031			
normal/grade 1	1097 (89.0%)	966 (89.9%)	54 (84.4%)	77 (81.1%)			0.190	0.033	0.687

	Overall	Groups			Overall significance test[a]		Pairwise comparisons[b]		
	Total (N=1234) n (%)	No Bone Grafting (n=1075) n (%)	1-Stage Bone Grafting (n=64) n (%)	2-Stage Bone Grafting (n=95) n (%)	χ^2	P value	None vs 1-stage	None vs 2-stage	1-stage vs 2-stage
grade 2	94 (7.6%)	73 (6.8%)	9 (14.1%)	12 (12.6%)			0.051	0.051	0.814
grades 3/4	37 (3.0%)	31 (2.9%)	1 (1.6%)	5 (5.3%)			--	0.338	--
Patella articular cartilage pathology					7.03	0.134			
normal/grade 1	866 (70.2%)	765 (71.2%)	45 (70.3%)	56 (58.9%)					
grade 2	239 (19.4%)	199 (18.5%)	14 (21.9%)	26 (27.4%)					
grades 3/4	128 (10.4%)	110 (10.2%)	5 (7.8%)	13 (13.7%)					
Trochlea articular cartilage pathology					3.40	0.493			
normal/grade 1	978 (79.3%)	860 (80.1%)	47 (73.4%)	71 (74.7%)					
grade 2	103 (8.4%)	85 (7.9%)	8 (12.5%)	10 (10.5%)					
grades 3/4	152 (12.3%)	129 (12.0%)	9 (14.1%)	14 (14.7%)					
Biologic Enhancement					0.17	0.919			
no	1116 (90.5%)	972 (90.5%)	58 (90.6%)	86 (90.5%)					
yes	112 (9.1%)	99 (9.2%)	5 (7.8%)	8 (8.4%)					

Key: Ns that do not sum to 1234 and percentages that do not sum to 100% reflect missing data.

BTB = bone-patellar tendon-bone; LFC = lateral femoral condyle; LTP = lateral tibial plateau; MFC = medial femoral condyle; MTP = medial tibial plateau.

[a] Chi-square test of association used to assess significance.

[b] Pairwise differences were tested using Z-tests of 2 proportions with Benjamini & Hochberg adjusted p-values. No adjusted pairwise p-values are reported for comparisons using cell size < 5.

[*] Rows with cell sizes of 0 and those that contributed to >20% of counts <5 are marked with an asterisk and were excluded from the overall significance test due to violation of assumptions.[28] Sensitivity analysis was conducted by leaving these small groups in. Results showed the same pattern of significance.

Table 6.

2-Year Patient-Reported Outcomes

Median (25%, 75% quartile) Two-Year Patient-Reported Outcome Scores	Overall (n=1052)	No Bone Grafting (n=917)	1-Stage Bone Grafting (n=58)	2-Stage Bone Grafting (n=77)	P Value
IKDC	77 (60, 86)	77 (61, 86)	72 (63, 86)	68 (48, 82)	**0.006** *1*
KOOS					
• Symptoms	79 (64, 89)	79 (64, 89)	82 (71, 92)	79 (60, 86)	0.31
• Pain	89 (75, 94)	89 (75, 94)	92 (78, 97)	88 (72, 95)	0.34
• Activities of Daily Living (ADL)	97 (88, 100)	97 (88, 100)	97 (90, 100)	96 (86, 99)	0.26
• Sports/recreation	75 (55, 90)	75 (55, 90)	75 (55, 85)	65 (35, 81)	**0.005** *2*
• Quality of life (QOL)	56 (38, 75)	63 (44, 75)	56 (44, 69)	44 (31, 63)	**0.002** *3*
WOMAC					
• Stiffness	75 (63, 100)	75 (63, 100)	88 (66, 100)	75 (50, 88)	0.13
• Pain	95 (80, 100)	95 (80, 100)	95 (85, 100)	95 (79, 100)	0.20
• Activities of Daily Living (ADL)	97 (88, 100)	97 (88, 100)	97 (90, 100)	96 (86, 99)	0.26
Activity Level (Marx)	7 (2, 12)	7 (2, 12)	6 (3, 11)	3 (1, 8)	**0.002** *4*

Key:

1: ANOVA tests showed a significant difference in this variable between groups (p=0.006). Tukey HSD multiple comparison test showed that the 2-stage bone grafting was significantly lower than the no bone grafting group (p=0.004). The 1-stage bone grafting group was not significantly different from the 2-staged bone grafting group (p=0.06) or the no bone grafting group (p=0.99).

2: ANOVA tests showed a significant difference in this variable between groups (p=0.005). Tukey HSD multiple comparison test showed that the 2-stage bone grafting was significantly lower than the no bone grafting group (p=0.003). The 2-stage bone grafting group was not significantly lower than the 1-stage grafting group (p=0.07).

3: ANOVA tests showed a significant difference in this variable between groups (p=0.002). Tukey HSD multiple comparison test showed that the 2-stage bone grafting was significantly lower than the no bone grafting group (p=0.001) and to the 1-stage bone grafting group (p=0.05). The 1-stage bone grafting group was not significantly different than the no bone grafting group (p=0.99).

4: ANOVA tests showed a significant difference in this variable between groups (p=0.002). Tukey HSD multiple comparison test showed that the 2-stage bone grafting was significantly lower than the no bone grafting group (p=0.001). The 2-stage bone grafting group was not significantly lower than the 1-stage grafting group (p=0.19).

Table 7.

Incidence of Subsequent Surgery at 2 Years

Incidence of Subsequent Surgery	Overall (n=1134)	No Bone Grafting (n=990)	1-Stage Bone Grafting (n=59)	2-Stage Bone Grafting (n=85)	P Value[1]
Subsequent Surgery	149 (13%)	127 (13%)	6 (10%)	16 (19%)	0.16
• Scope (meniscus, articular cartilage, hardware removal, etc)	106 (9%)	93 (9%)	5 (8%)	8 (9%)	
• ACL reconstruction	37 (3%)	29 (3%)	1 (2%)	7 (8%)	
• Total knee arthroplasty (TKA)	6 (<1%)	5 (<1%)	0 (0%)	1 (1%)	

Key: ACL = anterior cruciate ligament

[1]=Chi-square test of association used to assess significance (X^2=3.66)