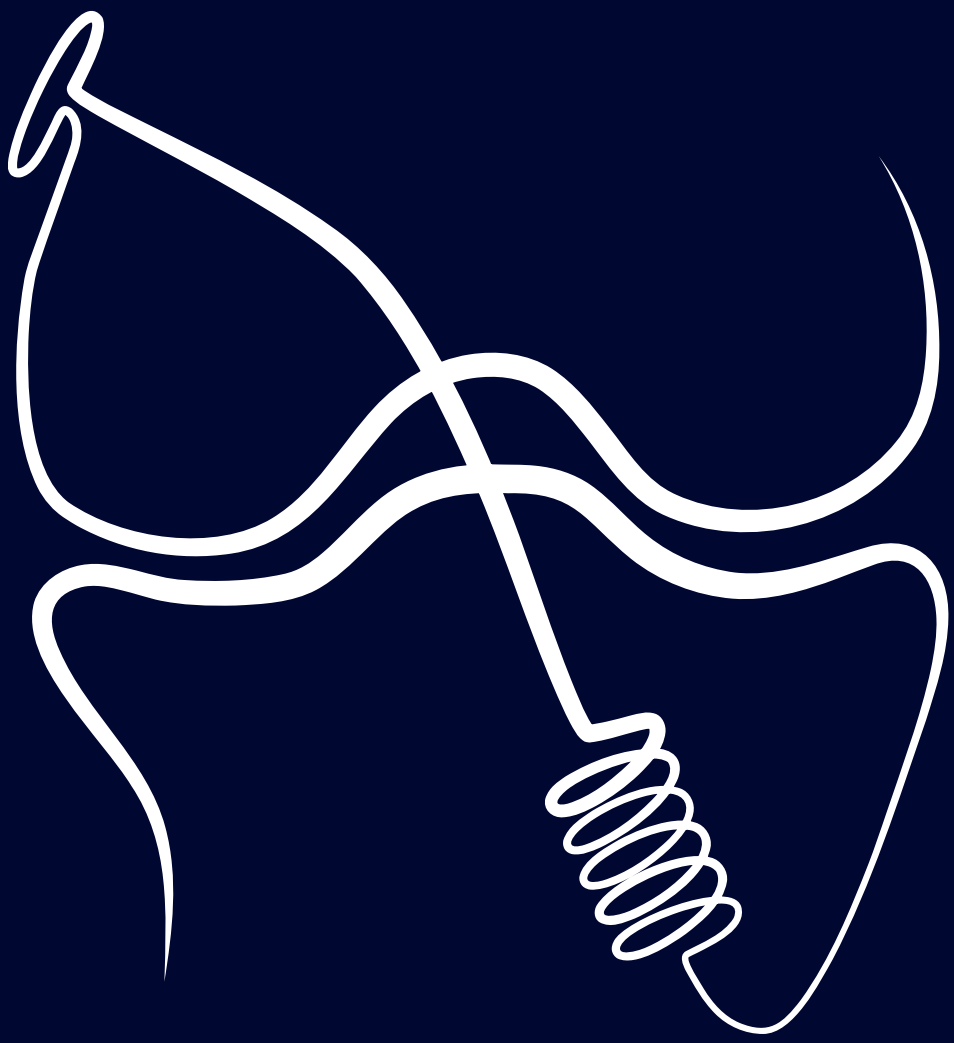
ANTERIOR CRUCIATE LIGAMENT REPAIR

THE QUEST CONTINUES…



R.A.G. HOOGESLAG

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THE QUEST CONTINUES

Roy Antonius Gerhardus Hoogeslag

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DISSERTATION

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on the authority of the rector magnificus,
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on account of the decision of the Doctorate Board
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CHAPTER 1

General Introduction

Anterior cruciate ligament of the knee

The anterior cruciate ligament (ACL) is one of the important passive stabilizers of the knee[23]. With a length of approximately 25–35 mm, it is positioned centrally in the joint. It attaches to the posterior aspect of the medial wall of the lateral femoral condyle and to the central-anterior aspect of the tibial plateau[6, 72]. It has a complex anatomy, consisting of a multitude of collagen-based fascicles forming a ribbon-like structure that has a reciprocal tensioning pattern, with one part tauter in knee-flexion and another part tauter in knee-extension.[1, 70, 71]. The ACL receives most of its blood supply proximally from the middle genicular artery and the remainder distally from the medial and lateral inferior genicular arteries[7, 63]. Its mechanoreceptors, which originate from the tibial nerve, detect knee joint position, movement and acceleration, aiding neuromuscular control of both the ipsilateral and the contralateral legs[65, 66]. Furthermore, it is covered with a synovial sheath which facilitates most of the blood and nerve supply and which keeps the ACL from coming into direct contact with the synovial fluid of the knee joint[6, 7, 63]. Due to its orientation, the ACL resists anterior tibial translation in relation to the femur[23]. Furthermore, it has a secondary function in resisting tibial internal, valgus and varus rotational forces on the knee joint[23].

Anterior cruciate ligament injury

Rupture of the ACL is one of the most common ligamentous injuries of the knee, with a reported incidence of 0.3 to 0.8 per 1,000[20, 21, 52, 62]. In the United States, more than 120,000 patients per year suffer from ACL injury, with approximately $1 billion in direct and indirect costs annually. In The Netherlands, it is estimated that around 10,000 patients per year suffer from ACL injury[31]. Most ACL injuries occur in active individuals in their late teens and early twenties during sporting activities, and the reported incidence of ACL injury in these age groups is increasing[24, 57, 62]. The most common trauma mechanism for an ACL injury does not involve direct contact to the knee; rather, the trauma occurs during a pivoting movement, with the knee in flexion, and with valgus stress and tibial internal rotation[13]. This type of trauma mechanism is associated with meniscal, medial collateral ligament, and anterolateral corner injury, which can result in increased knee loads and pathological knee kinematics if left untreated[76].

ACL injury often leads to increased laxity of the affected knee joint and reduced neuromuscular control[10, 11, 22, 33, 37, 73]. This may result in dynamic instability of the knee and is associated with an increased risk of concomitant cartilage lesions, meniscal lesions, and early-onset posttraumatic osteoarthritis[38-40, 50, 55]. These factors may result in a reduced activity level and can have immediate and long-term negative effects on knee-related quality

of life[38, 39, 50]. The overall goal in the treatment of patients with knee injury is therefore (1) rapid return to previous activity level with normal knee function and without residual complaints and (2) prevention of subsequent knee injuries and degenerative joint-disease[78].

Historical perspective on anterior cruciate ligament surgery: from repair to reconstruction

In the 20th century, primary suture repair of the ACL, re-approximating the ruptured ends, was described as a surgical treatment method for patients with ACL injury[18, 42]. The first case of ACL suture repair (ACLSR) was reported in 1902 by Mayo Robson, and in the following decades ACLSR was further popularized[53, 56, 60]. From the 1960s to the 1990s, several papers on the clinical outcomes of ACLSR were published[75]. Although short-term outcomes were reported to be excellent, in 1976 Feagin et al. noticed deterioration of midterm results, and in the years to follow their finding was echoed by several other authors[18, 32, 42, 54, 61]. In 1991, Sherman et al. suggested that there was a correlation between ACLSR for midsubstance ACL ruptures and inferior results and that ACLSR for proximal ACL ruptures might improve outcomes[69]. Furthermore, Sherman et al. defined a rationale for augmentation of the ACLSR to improve results in a subset of patients. Subsequently, however, better outcomes were reported for ACL reconstruction (ACLR) with an autologous patellar tendon graft than for ACLSR, and at the end of the 20th century this led to the abandonment of ACLSR techniques and the widespread adoption of ACLR as surgical treatment for ACL ruptures[16].

Current surgical gold standard: anterior cruciate ligament reconstruction

Today, most young athletes with ACL rupture opt for ACLR, the current surgical gold standard. In ACLR, the remnants of the ruptured ACL are debrided and replaced with a graft (...) typically from autologous hamstrings, bone-patellar-tendon-bone or quadriceps tendon (...), to restore the biomechanical stability of the knee joint (Figure 1). However, ACLR does not completely restore the ACL's complex native anatomy nor the native neuro-feedback, leaving the knee joint with some altered biomechanical and neurophysiological function[72, 81]. Although ACLR has been shown to be an effective treatment for ACL injury, half of patients do not return to competitive level sport, a third do not return to their pre-injury type of sports and a fifth do not return to sports at all[3-5, 12].

Moreover, a significant failure rate is reported after ACLR, especially in younger active patients, and there is substantial risk of sustaining injury to the contralateral native ACL[41, 79]. Furthermore, neither non-operative treatment nor ACLR prevent early-onset posttraumatic osteoarthritis. Given that ACL injuries mainly occurs in young, active individuals, this can have devastating effects even in the patient's thirties or forties[9, 38]. Thus, both historical ACLSR and the current treatment options fail to meet the overall purpose of the treatment of patients with ACL injury.

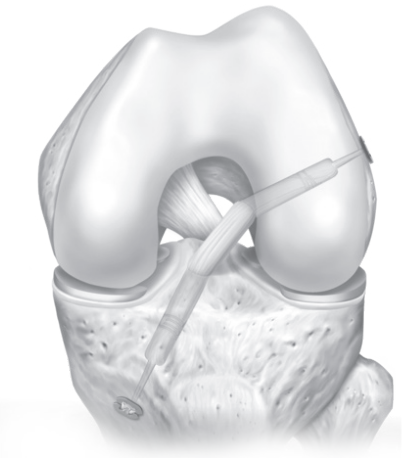

Figure 1. Reconstruction of the ACL. ACL reconstruction with quadrupled semitendinosus graft, all-inside technique with femoral and tibial sockets and femoral and tibial fixation and tensioning tibial with variable loop length cortical button fixation device.

Modern anterior cruciate ligament repair

To improve treatment results for patients with ACL injury, researchers have regained their interest in ACLSR in the last two decades. The potential advantages of ACLSR over ACLR include recovery of the complex native anatomy and proprioceptive function, the absence of donor site morbidity of the graft and reduction of the risk of early-onset posttraumatic osteoarthritis[78]. From research to understand the mechanisms that underlie the inability of the native injured ACL to heal, including animal model studies conducted in the 2000s, new insights into the biology and biomechanics of the ruptured ACL emerged[43]. It was shown that the ACL has excellent intrinsic healing potential[46, 51]. In contrast to extra-articular ligaments, however, no blot cloth is formed between the ruptured ends of the ACL to act as a provisional scaffold for cells to invade and remodel; it is flushed away by the synovial fluid, and diastasis occurs between the ruptured ends of the ACL with movement of the knee[2, 14, 33, 68, 74]. Subsequently, it was reported that ACLSR with the addition of a collagen

scaffold that bridges the ruptured ends of the sutured ACL could stimulate functional ACL healing with biomechanical properties equal to ACLR and that the short-term incidence of osteoarthritis was significantly lower than for ACLR[44, 47-49, 77].

As well as the biological stimulus, placement of a strong, small-diameter braid parallel to the ACL and fixed to the tibial and femoral bone (augmentation) instead of suturing of the ruptured ACL without augmentation (as in most historical ACLSR techniques) was found to play an important role in the outcome of ACLSR[19, 45, 67]. Augmentation of the sutured ACL with a small-diameter braid restrains residual anterior tibial translational force (which was found to persist after historical non-augmented ACLSR techniques) while leaving the native ACL tissue and attachment sites intact as much as possible[19, 58, 59]. Two modern augmentation techniques can be distinguished: one where a small-diameter braid parallel to the ACL is fixed to both the tibial and the femoral bone directly (static augmentation; SA; Figure 2) and one where the braid is fixed to an additional elastic link (a spring-in-screw mechanism) on the tibia to compensate for some length change of the augmentation braid across the arc of flexion of the knee (dynamic augmentation; DA; Figure 3)[35, 80]. In contrast to DA, however, it has been reported that SA did not restore anterior tibial translation to normal values directly after operation or after cyclic loading[34, 64]. In 2014, the first paper describing prospectively gathered outcomes of a modern ACLSR technique in humans was published. Eggli et al. reported excellent clinical and radiological outcomes one year after DA ACLSR with microfracture in the femoral notch (and no collagen scaffold) as the biological stimulus[15]. The evolving body of evidence, including animal model studies and the early prospective clinical case series, support further investigation of modern DA ACLSR as a surgical treatment for ACL ruptures.

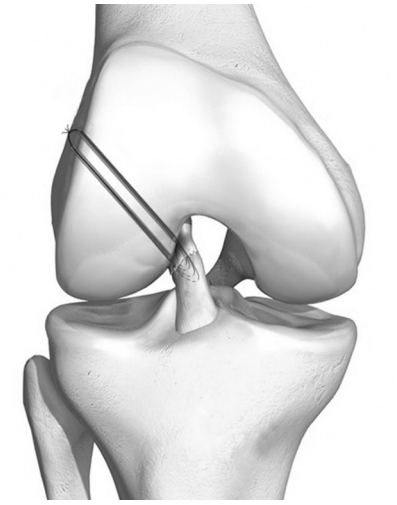

Figure 2. Non-augmented suture repair of the ruptured ACL. Looping sutures are placed through the tibial stump of the ruptured ACL, led through two femoral tunnels (in the posterolateral and anteromedial attachment of the ACL) and knotted over the lateral femoral cortex.

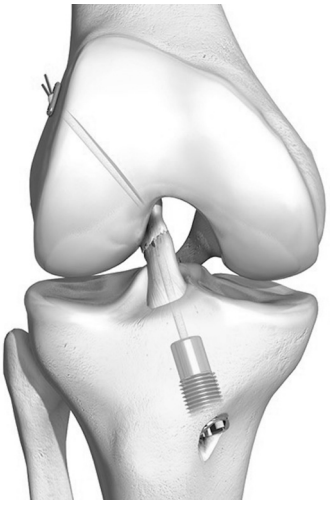

Figure 3. Dynamic augmentation of the ruptured ACL. ACL suture repair augmented with intraligamentary braid with cortical button fixation on the femoral side and additional elastic link (a spring-in-screw mechanism) on the tibial side.

Thesis aims and overview

The purpose of this thesis was to investigate the role of modern ACLSR in the treatment of ACL ruptures. The aims of the thesis were threefold: to review the literature on the clinical outcomes of modern ACLSR techniques; to investigate the role of augmentation in modern

ACLSR techniques and to compare augmented ACLSR with a non-augmented ACLSR technique commonly used in historical ACLSR studies; and to assess the early and midterm outcomes of modern DA ACLSR in relation to the current surgical gold standard, ACLR.

Chapter 2 presents a systematic review of the literature in which recent studies into clinical and patient-reported outcomes of several modern ACLSR techniques are summarized, critically appraised and compared[26].

Chapter 3 compares the biomechanical properties of two modern augmented ACLSR techniques and one historical non-augmented ACLSR technique in the human cadaveric knee, after cyclic loading and across the arc of flexion[28].

Chapter 4 assesses whether the targeted isometric tunnel placement for the ACL augmentation braid was attained. For an augmentation braid to function properly and not lead to slackening or over-constraining (and therefore length change of the suture repaired ACL) across the arc of flexion of the knee, it may be necessary to place the tunnels of the femoral and tibial augmentation isometrically[27].

Chapter 5 retrospectively investigates whether a preoperative magnetic resonance imaging (MRI) scan could have predicted specific morphological ACL rupture characteristics that were found during arthroscopic ACLSR[29]. In recent years, insights into patient selection criteria has led some authors to advocate repair of the ruptured ACL only when specific morphological rupture characteristics are present[8, 17, 36, 75]. Although a preoperative MRI scan can confirm rupture of the ACL in general, it is unknown whether an MRI scan can also confirm these specific ACL rupture characteristics, allowing the indication for ACLSR instead of ACLR to be determined preoperatively.

Chapter 6 presents the results at the two-year follow-up and **Chapter 7** presents the results at the five-year follow-up of a randomized controlled trial (RCT) comparing DA ACLSR to the current surgical gold standard, ACLR[25, 30].

Finally, **Chapter 8** of this thesis discusses the methods, results and implications of the presented studies, followed by recommendations for future research.

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CHAPTER 2

Efficacy of Nonaugmented, Static Augmented, and Dynamic Augmented Suture Repair of the Ruptured Anterior Cruciate Ligament; A Systematic Review of the Literature

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ABSTRACT

Background: Anterior cruciate ligament suture repair (ACLSR) was abandoned late last century in favor of anterior cruciate ligament (ACL) reconstruction (ACLR) because of overall disappointing results. However, in recent years there has been renewed and increasing interest in ACLSR for treatment of ACL ruptures. Several contemporary ACLSR techniques are being used, but any difference in effectiveness is unclear.

Null hypothesis: Contemporary nonaugmented (NA), static augmented (SA) and dynamic augmented (DA) ACLSR leads to (1) comparable outcomes overall and (2) comparable outcomes between proximal third, middle third and combined ACL rupture locations (a) within and (b) between ACLSR technique categories.

Study design: Systematic review.

Methods: An electronic search was performed in the MEDLINE and EMBASE databases for the period between January 1, 2010, and August 7, 2019. All articles describing clinical and patient-reported outcomes for ACLSR were identified and included, and outcomes for NA, SA, and DA ACLSR categories were compared.

Results: A total of 31 articles and 2422 patients were included. The majority of articles (65%) and patients (89%) reported outcomes of DA ACLSR. Overall, there was high heterogeneity in study characteristics and level as well as quality of evidence (19 level 4; 7 level 3; 3 level 2; and 2 level 1). Most studies indicated excellent patient-reported outcomes. Overall, the variability in (and maximum of) reported failure rate was high within all ACLSR categories. The variability in (and maximum of) reported rate of all other complications was highest for DA ACLSR. Regarding ACL rupture location, the failure rate was highest in proximal ACL ruptures within the SA and DA ACLSR categories; rates of all other reported complications were highest in combined ACL ruptures within the DA ACLSR category. However, no studies in the NA ACLSR category and only one study in the SA ACLSR category evaluated combined ACL ruptures. The majority of studies comparing ACLSR to ACLR found no differences in outcomes.

Conclusion: The amount of high-quality evidence for contemporary ACLSR is poor. This makes it difficult to interpret differences among ACLSR categories and among ACL rupture locations and, though promising, to establish the role of ACLSR in treatment of ACL ruptures. More high-quality large randomized clinical trials with longer follow-up comparing ACLSR to ACLR are needed.

INTRODUCTION

In the previous century, suture repair of the anterior cruciate ligament (ACL) was a commonly used treatment strategy to gain primary healing of the ruptured ACL.[56] In selected cases, good outcomes were achieved.[56] However, late last century, anterior cruciate ligament suture repair (ACLSR) was abandoned in favor of the current surgical gold standard, ACL reconstruction (ACLR). This paradigm shift was largely the result of poor outcomes following ACLSR, which became increasingly apparent at mid-term follow-up.[14, 16, 46]

In recent years, however, there has been renewed and increasing interest in ACLSR, as more insights into biology and biomechanics have emerged, and clinical series evaluating contemporary ACLSR techniques have been published.[15, 32, 42, 45, 56-58] As compared to ACLR, the proposed advantages of ACLSR are, among others, restoration of native anatomy, preservation of native proprioception, and lack of donor site morbidity.[5, 24, 29]

Two recent reviews focusing on proximal ACL ruptures deemed the quality and level of evidence for contemporary ACLSR to be low, and the risk of bias to be considerable.[45, 57] However, their conclusions were conflicting regarding the role of ACLSR for treatment of the (proximally) ruptured ACL. One of these reviews distinguished between results of different ACLSR techniques but only included studies evaluating mostly proximal ACL ruptures.[57] The other review did consider studies evaluating all ACL rupture locations but did not distinguish between outcomes for different ACLSR techniques.[45] Contemporary arthroscopic ACLSR can be nonaugmented (NA) or augmented with a small-diameter braid. In static augmented (SA) ACLSR, this braid is fixed directly to the tibial and femoral bone, whereas in dynamic augmented (DA) ACLSR, it is fixed to the femoral bone directly and to the tibial bone through an additional elastic link (spring-in-screw mechanism).[28] However, considerable debate exists as to which contemporary ACLSR technique is superior.[30, 57]

It is currently unknown whether there is an overall difference in outcomes between these ACLSR categories, and whether there is a difference in outcomes dependent of ACL rupture location.[45, 57]

Therefore, the purpose of this systematic review of the literature is to critically appraise, summarize, and compare recent literature on clinical and patient-reported outcomes of contemporary ACLSR and to compare results between NA, SA, and DA ACLSR techniques. The aim is to examine the following null hypotheses: contemporary NA, SA, and DA ACLSR

lead to (1) overall comparable outcomes and (2) comparable outcomes between proximal third, middle third and combined ACL rupture locations (a) within and (b) between ACLSR techniques, as measured by failure, revision ACL surgery, complication and reoperation rate, patient-reported outcomes, and knee laxity and function.

MATERIALS AND METHODS

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines were followed, and a PRISMA flow diagram was used.

Search strategy

On August 7, 2019, two of the authors (R.A.G.H. and R.W.B.) independently performed a comprehensive literature search in the MEDLINE/PubMed and EMBASE database. To include studies presenting on clinical and patient-reported outcomes for contemporary ACLSR techniques, the search was limited to articles published since January 1, 2010. The following key words in all fields and search strategy were used: (1) ACL, (2) anterior cruciate ligament, (3) 1 OR 2, (4) suture, (5) repair, (6) healing, (7) 4 OR 5 OR 6, and (8) 3 AND 7.

Inclusion and exclusion criteria

Original articles reporting clinical outcomes of contemporary primary ACLSR techniques (defined as arthroscopy-based ACLSR with or without augmentation, performed or published in the current decade) and available in the English, German, or Dutch language were included. Articles were excluded when they described outcomes of suture repair of partial ACL tears, ACLSR in patients with >2 ligamentous injuries, repair of ACL avulsion fractures and ACL ruptures treated with “healing response” without suture repair of the ruptured ACL stump. Articles solely describing surgical techniques or radiological outcomes without further clinical outcomes were also excluded, as were abstracts from scientific meetings, case reports, and review articles. In order not to overlook articles reporting high levels of complications at short-term follow-up, no minimum follow-up period was employed.

In case an identical patient cohort with identical outcomes and identical follow-up period was published in 2 articles, only the article with the highest level of evidence and critical appraisal (CA) was included. In the case of 2 articles reporting an identical patient cohort with different lengths in follow-up, only the article presenting outcomes with the longer follow-up period was included.

Review process

After removal of duplicates, 2 reviewers (R.A.G.H. and R.W.B.) independently evaluated the titles and abstracts of the identified articles for potential eligibility, assessed full texts of the selected potentially eligible articles for inclusion, and cross-checked the reference lists of the included articles to identify any that were not identified with the original electronic search. These articles underwent the same review process described earlier.

Data extraction

Two reviewers (R.A.G.H. and B.C.B.) independently extracted, summarized, and tabulated the following data: (1) study and patient characteristics, including biomechanical augmentation principle and rupture location quantified as proximal third, middle third, or distal third; (2) patient-reported outcomes; (3) knee laxity and knee function; and (4) complications (categorized as failure, ACL revision surgery, complication, reoperation, and hardware removal rate).

Quality assessment

Two reviewers (R.H.V and A.V.) independently rated the level of evidence and performed a CA. The level of evidence and study design were rated per the criteria of the Oxford Center of Evidence-Based Medicine.[48] The McMaster Critical Review Form for Quantitative Studies was used to rate the methodological quality of all study designs by assessing bias within studies.[36, 37] This form utilizes 9 categories: citation, study purpose, literature, design, sample, outcomes, intervention, results, and conclusions and implications. Responses were marked as yes (1 point), no or not addressed (0 points), or not applicable (item does not count). The sum of the outcomes (0 to a maximum of 14) divided by the sum of the applicable items reflects the overall quality of the study assessed.

Disagreement between reviewers was resolved by consensus, and a final decision by the third reviewer was not necessary.

Statistical analysis

The results of this review are presented as a qualitative synthesis. The extracted data are descriptively reported as means (standard deviation and/or minimum-maximum) and medians (interquartile range and/or minimum-maximum) for continuous variables and frequencies or percentages for categorical data.

To assess differences in outcomes between ACLSR techniques, the included studies were assigned to 1 of 3 pre-defined surgical technique categories (NA, SA, and DA), tabulated per the order of ACLSR category assignment, and, within each category, ranked in order of CA score from high to low.

Then, to compare outcomes between ACLSR categories, the overall variability per reported outcome measure for each category was summarized as range (minimum-maximum). If an included study compared ACLSR techniques from ≥2 ACLSR categories, assignment was based on that study's surgical gold standard, but if outcomes per ACLSR technique were specified, the reported outcomes were included in their respective ACLSR category. If an included study compared ACLSR techniques from ≥2 ACLSR categories without specifying the outcomes per category, study assignment was based on the category with the largest sample size at follow-up.

To assess differences in outcomes for ACL rupture location, within each ACLSR category the studies were assigned to a proximal third, a middle third, or a combined ACL rupture location group, and variability per reported outcome measure for each ACL rupture location group was summarized as range (minimum - maximum). If an included study did not specify the ACL rupture location, its outcomes were not considered for assessment of differences in outcomes for ACL rupture location.

RESULTS

Search results

The search of the MEDLINE/PubMed and Embase databases provided 4829 citations, of which 1735 were duplicates that were removed. The titles and abstracts of the remaining 3094 articles were reviewed, and 3048 articles were excluded, among which were 1 study that reported an identical patient cohort, follow-up period, and outcomes in 2 separate articles and 3 studies that covered an identical patient cohort with different lengths in follow-up.[2, 11, 12, 43] The full texts of the remaining 46 articles were reviewed, after which 18 articles were excluded. After cross-checking the references of the 28 eligible articles, 3 more studies were added. In total, 31 studies were included in this review (Figure 1).

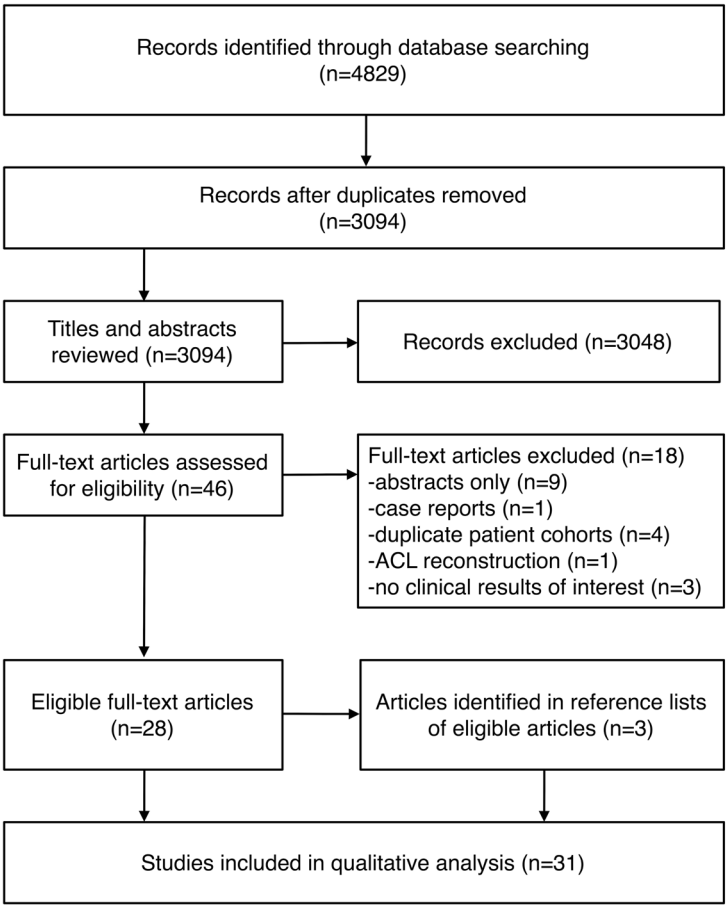

Figure 1. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flowchart for study inclusion.

Level of evidence and critical appraisal

Levels of evidence and CA scores are presented in Table 1 and Figure 2. The majority of included studies were Oxford level of evidence 4 (n=19 studies);[3, 6, 8-10, 13, 20, 22, 24-26, 33-35, 38, 39, 41, 47, 51] 7 studies were rated level 3;[1, 7, 15, 17, 19, 30, 55] 3 studies were rated level 2;[4, 23, 44] and only two studies were rated level 1.[27, 50] The largest number of studies with a high level of evidence (levels 1 and 2) was found for DA ACLSR. For NA ACLSR, the level of evidence of the studies was generally low (levels 3 and 4).

None met all of the McMaster CA criteria. Only 9 justified their choice of sample size before the study by means of a power calculation or descriptive justification (ie, first-in-human study).[1, 4, 7, 10, 15, 19, 27, 35, 50] Transparent and/or unbiased group assignment, to reduce the risk of contamination bias, was adequately addressed in just 4 studies.[7, 15, 27, 50] Furthermore, only 7 studies adequately addressed cointervention by providing information about the rehabilitation protocol and/or concomitant cartilage damage and multiligamentous knee injury.[8, 17, 26, 27, 33, 38, 44] In 14 studies, the statistical analysis was inadequate.[3, 6, 8, 9, 17, 19, 24, 34, 35, 39, 43, 47, 50, 55]

Study characteristics

Repair augmentation category. Table 1 presents the assignment of studies to ACLSR categories. All included studies could be assigned to 1 of the 3 predefined categories of contemporary ACLSR techniques (n=5, NA; n=6, SA; and n=20, DA). One study[30] compared results of NA to that study's gold surgical standard of SA ACLSR and was therefore categorized as SA ACLSR; however, for the summary of outcomes per ACLSR category, all outcomes for NA ACLSR were included in the NA ACLSR category. Another study compared the results of a combined NA and SA ACLSR group and an ACLR group, without reporting these outcomes separately per ACLSR category. Since the sample size for SA ACLSR was larger than that for NA ACLSR, this study was categorized as SA ACLSR.[55]

Patient population and study characteristics. Patient population and study characteristics are presented in Table 2. The vast majority of patients (2165 of 2422) were included in studies in the DA ACLSR category. Sample size varied vastly more for studies in the DA ACLSR category (8-455 patients) than for those in the NA and SA ACLSR categories, which were generally small (5-20 and 10-37 patients, respectively). Time from injury to surgery varied more in studies in the NA and SA ACLSR categories (6-81 and 21-89 days, respectively) than in those in the DA ACLSR category (10-18 days).

Approximately two-thirds of the included studies (n=21) reported a minimum mean follow-up of 24 months, of which 3 had a high level of evidence (level 1 and 2); 1 study on SA ACLSR and 2 on DA ACLSR.[23, 27, 44] The remaining 10 all had a mean follow-up of ≤12 months, of which 1, on DA ACLSR, had a high level of evidence.[50]

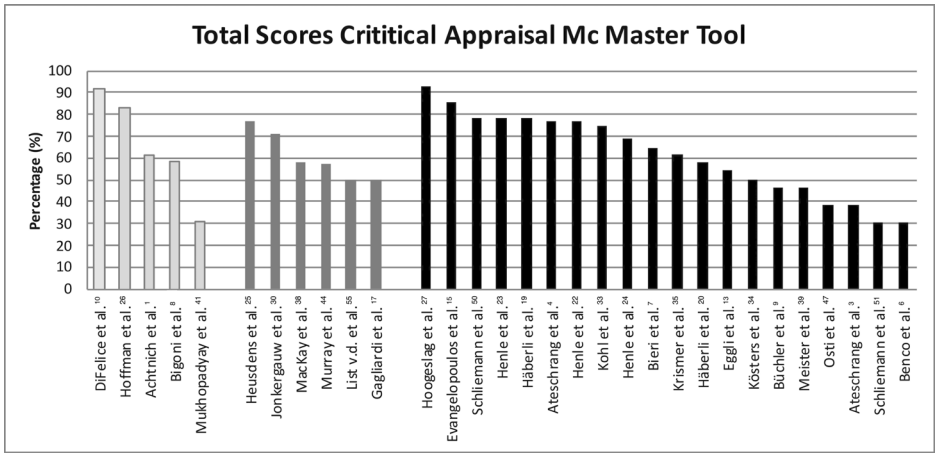

Figure 2. Overview of critical appraisal score (percentage) per anterior cruciate ligament suture repair (ACLSR) category: light grey columns, nonaugmented; dark grey columns, static augmented; black columns, dynamic augmented.

Two categories of biological stimuli to enhance healing of the sutured ACL were identified. Twenty-five studies reported bone marrow access only (abrasion of the femoral ACL attachment or microfracture in the femoral notch).[1, 3, 4, 6-8, 10, 13, 17, 20, 22, 24-27, 30, 33-35, 38, 39, 41, 47, 50, 55] Five studies (in the SA and DA ACLSR categories) indicated an additional collagen scaffold that bridged the femoral and tibial ACL stump as biological stimulus.[9, 15, 19, 23, 44]

ACL rupture location. All studies within the NA and SA ACLSR category (n=5 and n=6, respectively) and the majority of studies within the DA ACLSR category (n=18) could be assigned to 1 of the 3 predefined groups of ACL rupture location (n=13, proximal third; n=1, middle third; and n=15, combined). Notably, all but 1 of the included studies on SA ACLSR and all on NA ACLSR evaluated solely proximal third ACL rupture locations.[44] Therefore, no differences in outcomes among ACL rupture location groups could be assessed within the NA ACLSR category and between the NA ACLSR and other ACLSR categories.

In contrast, in the majority of the studies in the DA ACLSR category, there was a combined ACL rupture location.[9, 13, 22-24, 27, 33-35, 39, 47] Only 1 study evaluated solely middle third ruptures (DA ACLSR with and without an additional collagen scaffold).[15] Therefore, for the middle third ACL rupture location group no differences in outcomes between ACLSR categories could be assessed.

Table 1. Level of evidence of studies, arranged in order of critical appraisal score (high-low) per anterior cruciate ligament suture repair category[a].

				Critical Appraisal[b]														
	Year	LEO	Design	1	2	3	4	5	6	7	8	9	10	11	12	13	14	T/A[c]	%
NA ACLSR																			
DiFelice[10]	2018	4	case series	1	1	1	1	1	1	1	N/A	0	N/A	1	1	1	1	11/12	92
Hoffmann[26]	2019	4	case series	1	0	1	0	1	1	1	N/A	1	N/A	1	1	1	1	10/12	83
Achtnich[1]	2016	3b	case control study	1	0	0	1	1	1	0	0	0	1	1	1	1	0	8/13	62
Bigoni[8]	2017	4	case series	1	0	1	0	0	1	1	N/A	1	N/A	0	1	1	0	7/12	58
Mukhopadhyay[41]	2018	4	case series	0	0	0	0	0	1	1	N/A	0	0	1	0	1	0	4/13	31
SA ACLSR																			
Heusdens[25]	2018	4	poor quality cohort	1	1	0	0	1	1	1	N/A	0	1	1	1	1	1	10/13	77
Jonkergouw[30]	2019	3b	case control study	1	1	1	0	1	1	1	-	0	1	1	1	1	0	10/14	71
MacKay[38]	2015	4	poor quality cohort	1	0	0	N/A	1	1	0	N/A	1	1	1	0	1	0	7/12	58
Murray[44]	2019	2b	prospective cohort study	1	1	0	0	1	1	0	-	1	1	0	1	0	1	8/14	57
vd List[55]	2017	3b	case control study	1	1	0	0	1	1	1	-	0	1	-	0	0	1	7/14	50
Gagliardi[17]	2019	3b	case control study	1	0	0	0	1	-	1	0	1	1	0	1	0	1	7/14	50
DA ACLSR																			
Hoogeslag[27]	2019	1b	randomized controlled trial	1	1	1	1	1	1	1	1	1	1	1	1	0	1	13/14	93
Evangelopoulos[15]	2015	3b	case control study	1	1	1	1	1	1	1	1	0	1	1	1	0	1	12/14	86
Schliemann[50]	2017	1c	randomized controlled trial	1	1	1	1	-	1	1	1	0	1	1	1	0	1	11/14	79
Henle[23]	2018	2b	prospective cohort study	1	1	1	0	1	1	1	0	0	1	1	1	1	1	11/14	79
Haberli[19]	2019	3b	case control study	1	1	1	1	1	1	1	-	0	1	0	1	1	1	11/14	79
Ateschrang[4]	2018	2b	prospective cohort study	1	1	1	1	-	1	-	N/A	0	1	1	1	1	1	10/13	77
Henle[22]	2018	4	poor quality cohort	1	1	1	0	1	1	1	N/A	0	1	1	1	0	1	10/13	77
Kohl[33]	2016	4	poor quality cohort	0	1	1	N/A	1	1	1	N/A	1	1	1	1	0	0	9/12	75
Henle[24]	2015	4	poor quality cohort	1	1	1	0	1	1	1	N/A	0	1	-	1	0	1	9/13	69
Bieri[7]	2017	3b	case control study	1	1	0	1	-	-	1	1	-	0	1	1	1	1	9/14	64
Krismer[35]	2017	4	poor quality cohort	1	1	1	1	-	1	0	N/A	0	1	0	1	0	1	8/13	62

Table 1. Continued.

				Critical Appraisal[b]															
	Year	LEO	Design	1	2	3	4	5	6	7	8	9	10	11	12	13	14	T/A[c]	%
Haberli[20]	2018	4	poor quality cohort	1	1	1	N/A	1	1	0	N/A	0	N/A	1	1	0	0	7/12	58
Eggli[13]	2016	4	case series	0	0	1	N/A	1	1	0	N/A	0	N/A	1	0	1	1	6/11	55
Kösters[34]	2015	4	poor quality cohort	1	1	0	N/A	-	1	1	N/A	0	0	0	1	0	1	6/12	50
Büchler[9]	2016	4	poor quality cohort	0	1	1	0	-	1	1	N/A	0	1	0	0	1	0	6/13	46
Meister[39]	2017	4	poor quality cohort	1	0	1	0	1	1	0	N/A	0	1	0	1	0	0	6/13	46
Osti[47]	2018	4	poor quality cohort	0	1	1	0	-	-	1	N/A	0	1	0	1	0	0	5/13	38
Ateschrang[3]	2017	4	poor quality cohort	1	1	1	0	-	-	1	N/A	0	0	0	1	0	0	5/13	38
Schliemann[51]	2016	4	poor quality cohort	0	1	0	0	-	-	1	N/A	0	0	0	0	1	1	4/13	31
Benco[6]	2018	4	poor quality cohort	0	0	1	0	0	1	0	N/A	0	0	0	1	1	0	4/13	31

[a]Level of evidence (LOE) according to the Oxford Center of Evidence-Based Medicine criteria and critical appraisal according to the McMaster Critical Review Form for Quantitative Studies. ACLSR, anterior cruciate ligament suture repair; DA, dynamic augmented ; NA, non-augmented; SA, static augmented.

[b]Critical appraisal items were rated as yes (1), no (0), or not addressed (-) or not applicable (N/A); 1, study purpose clearly stated; 2, relevant background literature reviewed; 3, sample described in detail; 4, sample justified; 5, outcome measure reliably reported; 6, outcome measure validly reported; 7, intervention described in detail; 8, contamination avoided; 9, co-intervention avoided; 10, results reported in terms of statistical significance; 11, appropriate analysis methods; 12, clinical importance reported; 13, drop-outs reported; 14, appropriate conclusion.

[c]T = sum of CA items scored / A = sum of applicable CA items. % = T/A*100%;

Table 2. Study characteristics and complications, arranged in order of CA score (high-low) per anterior cruciate ligament (ACL) suture repair (SR) category[a].

Study (Year)	SG	Patients, n	FU, mo	Age, y	Comparison	Biological Stimulus	Rupture Location PT/MT/DT, %	Delay Injury – Surgery, d	Failure Rate, %	RAS Rate, %	Complication Rate[b], %	Reoperation Rate[c], %	HR+ Overall / Medical, %
NA ACLSR													
DiFelice[10, d] (2018)		10	72 ±218 (58-110)	37 ± 12 (17-57)	none	abrasion	100 / – / –	39 ± 28 (10-93)	9			10	
Hoffmann[26, d] (2017)		12	79 ±9– (60-98)	43 ± 13 (19-67)	none	micro#	100 / – / –	6 ± – (1-20)	25	8	0		
Achtnich[1, d] (2016)		20	28 ±8– (24-31)	30 ± 9 (–)[e]	ACLR	micro#	100/ – / –	< 42	15[e]	5[f]	0[f]	15[f]	
Bigoni[8, d] (2016)		5	43 ±315 (25-56)	9 ± – (8-10)	none	abrasion	100 / – / –-	81 ± – (15-123)	0	0	0	0	
Mukhopadhyay[41, d] (2018)		13	31 ±1– (26-38)	31 ± – (21-40)	none	abrasion & micro#	100 / – / –	8 ± – (3-12)	0	0	0	0	
Overall		*5-20*		*9-43*					*0-25[g]*	*0-8[g]*	*0-0[g]*	*0-15[g]*	*0-0 / -[g]*
Proximal third									*0-25[g]*	*0-8[g]*	*0-0[g]*	*0-15[g]*	*0-0 / -[g]*
Middle third													
Combined													
SA ACLSR													
Heusdens[25, d] (2018)		37	24	33 ± 15 (14-60)	none	micro#	100 / – / –	< 90	5	5			
Jonkergouw[30, d, g] (2019)	NA	25[g]	48[g] ±84 (24-108)	37 [g] ± 11 (–)	NA ACLSR	abrasion	100 / – / –	38[g, h] ± – (9-4018)	14[g]	7[g]		7 [g]	0 / -[g]
	SA	25	29[i] ±28 (24-108)	30 [i] ± 10 (–)				26[g, e] ± – (5-155)	7[e]	7[e]		0 [e]	7 / -[e]
MacKay[38] (2015)		27	12	34 ± 16 (16-60)	none	micro#	100 / – / –	<90	2	2	2	4	
Murray[44, d] (2019)		9	24	24[e] ± 5 (18-35)	ACLR	COL	10 / 90 / –	20[e] ± 5 (11-28)	0	0	0 [f]	10[f]	10 / -[f]
vd List[55] (2017)		52	6	33[i] ± 11 (14-57)	ACLR	abrasion	100 / – / –	48[i] ± 39 (5-155)	2[e]	2[e]	2[e]	0[e]	
Gagliardi[17, d] (2019)		22	32[e, h] (24-43) (–)	14[e] ± 3 (–)	ACLR	micro#	100 / – / –	34[e] ± – (18-67)	49[i]		2[e]		
Overall		*9-52*		*14-34*					*0–49*	*0-7*	*0-2*	*0-10*	*7-10 / -*
Proximal third									*2-49*	*2-7*	*2-2*	*0-4*	*7-7 /-*
Middle third													
Combined									*0-0*	*0-0*	*0-0*	*10-10*	*10-10 / -*
DA ACLSR													
Hoogeslag[27, d] (2019)		23	24	21[e, h] (18-27) (–)	ACLR	micro#	83 / 13 / 4	13[h, i] (12-16) (–)	8[e]	8[f]	21[e]	21[e]	9 / 9[f]
Evangelopoulos[15, d] (2017)	COL+	23	24	30 ± 11 (–)	COL+ / COL-	micro# & COL	– / 100 / –		0	0	9	9	
	COL-	33		27 ± 10 (–)					18[i]	18[f]	61[f]	33[f]	
Schliemann[50] (2017)		30	12	28[e] ± 11 (–)	ACLR	micro#		15[e] ± 5 (–)					
Henle[23, d] (2018)	DS+	46	26 ±65 (24-46)	32 ± 10 (–)	none	micro# & COL	81 / – / –	14 ± 4 (–)	13	13		19	
	DS-	39		31[e] ± 9 (–)			84[e] / – / –	13[e] ± 5 (–)	9[e]	9[e]		12[f]	
Haberli[19, d] (2019)	HR+	47	24 ±42 (–)	34 ± 15 (–)	none	micro# & COL		<21					
	HR-	126		34[e] ± 10 (–)									
Ateschrang[4, d] (2018)	1I	50	28 ±810 (–)	30 ± 10 (27-33)	none	micro#	100 / – / –	20 ± 12 (17-23)	4	13			
	2R	52		26 ± 10 (23-29)				16 ± 7 (14-18)	27[i]				
	>2R	24		26[i] ± 8 (22-30)				19[e] ± 9 (15-23)	27[i]				
Henle[22, d] (2018)	RAS+	381	30	22 ± 7 (–)	none	micro#	57 / 43 / –	18 ± 9 (–)	8	8			20 / -
	RAS-			34[i] ± 12 (–)			76[e] / 24[e] / –	16[e] ± 7 (–)					40 / -[e]

Table 2. Continued.

Study (Year)	SG	Patients, n	FU, mo	Age, y	Comparison	Biological Stimulus	Rupture Location PT/MT/DT, %	Delay Injury – Surgery, d	Failure Rate, %	RAS Rate, %	Complication Rate[b], %	Reoperation Rate[c], %	HR+ Overall / Medical, %
Kohl[33, d] (2016)		50	24	30 ± 18-50 (–)	none	micro#	80 / 20 / –	11 ± – (1-21)	10	8	12	10	60 / 34
Henle[24, d] (2015)		62	24	32 ± 11 (18-63)	none	micro#	73 / 26 / 1	18 ± 0 (–)	4	3	4		24 / 14
Bieri[7, d] (2017)		53	24	30[e] ± 9 (–)	ACLR	micro#		14[i] ± 13 (–)	11[f]	11[e]	13[f]	20[f]	36 / -[i]
Krismer[35, d] (2017)	RE#+ RE#-	36 228	24	23 ± 8 (–) 32[i] ± 12 (–)	none	micro#	58 / 39 / 3 80 / 38 / 2[i]	12 ± 9 (–) 12[e] ± 10 (–)	14	10	2[b]	2	35 / -
Haberli[20, d] (2018)		455	28 ±8– (21-64)	33 ± 12 (–)	none	micro#			9	9	9	17	31 / 25
Eggli[13, d] (2016)		8	60	23[h] (–) (19-41)	none	micro#	30 / 70 / –	10[h] (–) (5-13)[h]	20	20	30		40 / 30
Kösters[34] (2015)		26	12	30 ± – (16-65)	none	micro#	96 / 4 / –	16 ± – (2-51)	2	2	8	8	8 / 8
Büchler[9] (2016)		42	12	26[h] (10) (18-54)	none	micro# & COL	73 / 27 / –	13 ± 6 (1-21)	7	7			
Meister[39] (2017)		26	12	28 ± 9 (18-50)	none	micro#	62 / 30 / 8	15 ± 5 (4-25)	15		35	27	42 / -
Osti[47] (2018)		57	12	28 ± 9 (15-54)	none	micro#	84 / 14 / 2	15 ± 5 (2-29)	18	5	37	23	35 / 12
Ateschrang[3] (2017)		32	12	28 ± 9 (–)	none	micro#	100 / – / –	17 ± 7 (–)	16		9		- / 2
Schliemann[51] (2016)		180	12	30 ± – (16-64)	none				3	3			
Benco[6] (2018)		38	12	31 ± – (15-61)	none	micro#	100 / – / –	14 ± – (–)	1		8	4	15 / -
Overall		*8-455*		*21-34*					*0-27*	*0-20*	*2-61*	*2-33[c]*	*9-60 / 9-34*
Proximal third									*1-27*	*13-13*	*8-9*	*4-4*	*15-15 / 2-2*
Middle third									*0-18*	*0-18*	*9-61*	*9-33*	-
Combined									*2-20*	*2-20*	*2-37*	*2-27*	*9-60 / 9-34*

[a]Outcomes are reported as mean ± SD (range minimum-maximum) unless otherwise indicated. Overall variability and variability for proximal third, middle third and combined anterior cruciate ligament rupture location per outcome measure are summarized as range. 1I, one bundle, intact synovial sheath; 2R, 2 bundles, ruptured synovial sheath; abrasion, abrasion of the femoral ACL attachment; ACLR, anterior cruciate ligament reconstruction; ACLSR, anterior cruciate ligament suture repair; COL, bridging collagen scaffold; DA, dynamic augmented; DS, designer surgeon; DT, distal third of the ACL; FU, follow-up; HR, hardware removal; micro#, microfracture of the femoral notch; MT, middle third of the anterior cruciate ligament; NA, non-augmented; PT, proximal third of the ACL; RAS, revision anterior cruciate ligament surgery; RE#, rerupture; SA, static augmented; SG, subgroup;

[b]For reasons other than failure.

[c]For reasons other than revision ACL surgery or hardware removal.

[d]Minimum (mean or median) follow-up of 24 months.

[e]No statistically significant difference.

[f]Statistical significance not reported.

[g]Study reported results for NA and SA ACLSR; results for NA ACLSR group were included in the NA ACLSR category.

[h]Median (interquartile range) (range: minimum-maximum).

[i]Statistically significant difference.

Outcomes

Failure, revision ACL surgery, complication and reoperation rates. Failure and complications are presented in Table 2. The majority of the included studies reported failure, revision ACL surgery, complication, and reoperation rates, while predominantly those in the DA ACLSR category indicated hardware removal rate.

In general, the variability in reported failure rates was high within all ACLSR categories, and the maximum reported failure rate was highest in the SA ACLSR category (NA, 0-25%; SA, 0-49%; DA, 0-27%). For revision ACL surgery (NA, 0-8%; SA 0-7%; DA, 0-20%), complications (NA, 0-0%; SA, 0-2%; DA, 2-61%) and reoperations (NA, 0-15%; SA, 0-10%; DA, 2-33%), the variability in (and maximum of) reported rates were highest within the DA ACLSR category.

Regarding outcomes with respect to ACL rupture location, within both the SA and the DA ACLSR categories, the proximal third rupture group had highest variability in reported failure rates, and the maximum reported failure rate was highest in the SA category. In contrast, within the DA ACLSR category, the middle third and combined rupture group had highest and alike variability in (and maximum of) reported revision ACL surgery, complication and reoperation rate. Within the NA and SA ACLSR categories, for proximal third and combined ACL rupture location groups this was alike and the maximum reported rates were lower compared to the DA ACLSR category.

Regarding hardware removal rate, only studies in the DA ACLSR category differentiated between reasons for hardware removal.[13, 20, 24, 27, 33, 34, 47] In the majority of studies, the overall hardware removal rate was higher than that for medical reasons (eg, local pain or tenderness at the tibial screw insertion site).[13, 20, 24, 33, 47]

Patient-reported outcomes. Patient-reported outcomes are presented in Table 3. The most frequently presented patient-reported outcomes at follow-up were the Tegner Activity Scale (TAS), IKDC Subjective (IKDCs), and Lysholm score.

Only a minority of the studies presented preinjury subjective outcome scores, except for the TAS, which was included in the majority (n = 19) of studies in the DA ACLSR category.

Of all studies for which the TAS at follow-up minus the pre-injury TAS could be calculated, 14 found a decrease (ie, a decrease in activity level) and 3 reported no difference. The

middle third rupture location group of the DA ACLSR category had the highest maximum of reported differences in follow-up minus preinjury TAS. This resulted from 1 study; however this study did indicate improvement of the delta between the TAS at follow-up and the preinjury TAS (of -1.0 instead of -2.5) if a bridging collagen scaffold was added to middle third ACL ruptures in DA ACLSR.[15]

Overall, the variability in reported IKDCs and Lysholm scores at follow-up was low within and similar among all ACLSR categories, and all scores were high. Variability was similar among all ACL rupture location groups within and among ACLSR categories, except for the Lysholm score in the SA category, for which no comparative data among ACL rupture location groups were available.

Minimum scores at baseline for some studies were low for IKDCs in the SA and DA ACLSR categories and for Lysholm in the NA and DA ACLSR categories. This was caused by studies that evaluated preoperative instead of pre-injury baseline scores.[27, 39, 41, 44]

Knee laxity and knee function. Knee laxity and knee function outcomes are presented in Table 3. A majority of studies in the NA (n = 4) and DA (n = 13) ACLSR categories and a minority of studies in the SA ACLSR category (n = 2) reported side-to-side differences in the Lachman test. Overall, the variability in these differences was low within and similar among all ACLSR categories, and the reported differences were small. Furthermore, variability in side-to-side differences was similar among all ACL rupture location groups within and among all ACLSR categories.

In addition, knee function at follow-up – in terms of the IKDC 2000 physical examination grade – was at grade A or B in the majority of patients; however, it was included in only 8 of the reviewed studies (mostly of high level and quality).[1, 10, 26, 27, 30, 39, 44]

Table 3. Objective and subjective outcomes, arranged in order of critical appraisel score (high-low) per anterior cruciate ligament suture repair category[a]

	SG	Tegner			IKDCs			Lysholm				IKDCpe A / B (%)
		Baseline	FU	Δ	Baseline	FU	Δ	Baseline	FU	Δ	Δ LM, mm	
NA ACLSR												
DiFelice[10, b]		7.2 ± 1.2 (5-9)	6.6 ± 1.8 (3-9)	-0.6		92 ± 11 (65-100)			96 ± 5 (88-100)			90 / 10
Hoffmann[26, b]		6.3 ± (1.5, –)	5.2 ± 1.8 (–)	-1.1		87 ± 17 (–)			85 ± 20 (–)		2.1 ± 1.3 (1-5)	73 / 9
Achtnich[1, b]											1.95[c] ± 1.7 (–)	65 / 20[c]
Bigoni[8, b]						93 (–) (68-95)			94 ± – (68-100)		3.0 ± 0.7 (2-4)	
Mukhopadhyay[41, b]								36[d] ± 5 (30-47)	95 ± 1 (94-96)	59[d]	1.7 ± 0.8 (1-3)	
Overall		*6.3-7.2*	*5.2-6.6[e]*	*-1.1 - -0.6*		*87-93*		*36-36*	*85-96*	*+59*	*1.7-3.0*	*A+B: 75-100*
Proximal third		*6.3-7.2*	*5.2-6.6[e]*	*-1.1 - -0.6*		*87-93*		*36-36*	*85-96*	*+59*	*1.7-3.0*	*A+B: 75-100*
Middle third			-									*A+B: –*
Combined			-									*A+B: –*
SA ACLSR												
Heusdens[25, b]												
Jonkergouw[30, b, e]	NA	6.4[e] ± 1.4 (–)	6.0[e] ± 1.3 (–)	-0.4[e]		91[e] ± 12 (–)			95[e] ± 7 (–)			73 / 15
	SA	7.0[c] ± 1.6 (–)	6.4[c] ± 1.7 (–)	-0.6		89[c] ± 10 (–)			93[c] ± 8 (–)			
MacKay[38]												
Murray[44, b]					35[f, d] ± 11 (–)	92[c] ± 12 (–)	+57[d]				1.9[f] ± 2.1 (–)	44 / 56[f]
vd List[55]												
Gagliardi[17, b]						91[c, g] (84-98) (–)			100[c, g] (90-100) (–)		2.0[c, g] (2-2) (–)	
Overall		*7.0-7.0*	*6.4-6.4*	*-0.6-0.6*	*35-35*	*89-92*	*+57*		*93-100*		*1.9-2.0*	*A+B: 88-100*
Proximal third		*7.0-7.0*	*6.4-6.4*	*-0.6-0.6*		*89-91*			*93-100*		*2.0-2.0*	*A+B: 88-88*
Middle third					*35-35*		*+57*				-	*A+B: –*
Combined						*92-92*					*1.9-1.9*	*A+B: 100-100*
DA ACLSR												
Hoogeslag[27, b]		8.0[c, g] (7- (–)	7.0[c, g] (5-9) (–)	-1.0	72[c, d, g] (49-95 (–)	95[c, g] (81-100) (–)	+23[d]				1.0[c, g] (0.8-2.0) (–)	87 / 13[c]
Evangelopoulos[15, b]	COL+	7.0[g] (–) (4-8)	6.0[g] (–) (4-10)	-1.0				100[g] (–) (97-100)	100[g] (–) (93-100)	0	1.0[g] (–) (-1 to 3)	
	COL-	7.5[c, g] (–) (4-7)	5.0[c, g] (–) (4-9)	-2.5				100[c, g] (–) (96-100)	95[g, h] (–) (60-100)	-5	1.0[g, c] (–) (-2 to 5)	
Schliemann[50]		6.1[c] ± 1.6 (4-10)			94 [c] ± 10 (–)	86[c] ± 12, (–)	-8	97[c] ± 5 (–)	90[c] ± 11 (–)	-7	1.7[c]	
Henle[23, b]	DS+	5.0[d] ± 1 (–)	5.0 ± 2.0 (–)	0[d]		94 ± 8 (–)			96 ± 6 (–)			
	DS-	6.0[d, h] ± 2.0 (–)	5.0[c] ± 2.0 (–)	-1.0[d]		87[h] ± 14 (–_			90[h] ± 12 (–)			
Haberli[19, b]	HR+		5.2 ± 2.2 (–)			97 ± 8 (–)		96 ± 7 (–)	99 ± 4 (–)	+3	1.5 ± 2.2 (–)	
	HR-		4.8[c] ± 1.2 (–)			97[c] ± 4 (–)		96[c] ± 5 (–)	98[c] ± 3 (–)	+2	2.0[c] ± 1.7 (–)	
Ateschrang[4, b]	1I	5.0 ± – (1-9)										
	2R	5.0[c] ± – (1-9)										
	>2R	3.0 [c] ± – (1-9)										

Table 3. Continued.

	SG	Tegner			IKDCs			Lysholm				IKDCpe A / B (%)
		Baseline	FU	Δ	Baseline	FU	Δ	Baseline	FU	Δ	Δ LM, mm	
Henle[22, b]	RAS+ RAS-	6.0 ± 2.0 (–) 5.0[h] ± 1.0 (–)									3.2 ± 2.0 (–) 1.7[h] ± 1.9 (–)	
Kohl[33, b]		6.0[g] (–) (6.0-7.0)	6.0[g] (–) (5.0-7.0)	0		98[g] (–) (95.0-100)			100[g] (–) (98-100)		1.2 ± – (-1 to 6)	
Henle[24, b]		5.2 ± 1.3 (–)	5.1 ± 1.4 (–)	-0.1	99 ± 2 (–)	95 ± 6 (74-100)	-4	99 ± 2 (–)	97 ± 5 (–)	-2	2.1 ± 1.7 (–)	
Bieri[7, d]												
Krismer[35, b]	RE#+ RE#-	8.0[g] (7.0-9.0) (–) 7.0[g, h] (3.0-10.0)										
Haberl[20, b]		5.1										
Eggli[13, b]		6.0[g] (–) (4-9)	5.5[g] (–) (5-7)	-0.5	100[g] ± – (100-100)	99[g] (–) (79-100)	-1	100[g] ± (–) (100-100)	100[g] (–) (90-100)	0	2.0[g] (–) (0.0-4.0)	
Kösters[34]		6.0 ±	4.8	-1.2	97	88	-9	100	92	-8	1.7 ± 2.6 (–)	
Büchler[9]		7.0[g] (–) (4-9)	7.0[g] (–) (4-9)	0		90 ± 7 (–)					0.0 ± 1.6 (–)	
Meister[39]		8.0[g] (–) (6-10)	7.0[g] (–) (3-10)	-1.0				28[d] ± 14.0 (–)	94 ± 11 (–)	+66[d]		64 / 18
Osti[47]		7.0[g] (–) (4-9)	5.0[g] (–) (0-9)	-2.0								
Ateschrang[3]		6.0[g] (–) (1-10)	5.5[g] (–) (3-10)	-0.5	100[g] (–) (85-100)	94[g] (–) (55-100)	-6	100[g] (–) (88-100)	100[g] ±(–) (64-100)	0	2.1 ± 2.2 (-2 to 5)	42 / 45
Schliemann[51]		5.3	4.4	-0.9							1.3	
Benco[6]		7.1 ± – (2-10)	6.4 ± – (4-9)	-0.7		91 (–) (76-100)		99 ± – (90-100)	93 ± – (70-100)	-5.7		
Overall		*3.0-8.0*	*4.4-7.0*	*-2.5-0*	*72-100*	*86-99*	*-9-23*	*28-100*	*90-100*	*-8-66*	*0.0-3.2*	*A+B: 82-100*
Proximal third		*3.0-7.1*	*5.5-6.4*	*-0.7- -0.5*	*100-100*	*91-94*	*-6-6*	*99-100*	*93-100*	*-6-0*	*2.1-2.1*	*A+B: 87 -87*
Middle third		*7.0-7.5*	*5.0-6.0*	*-2.5- -1.0*				*100-100*	*95-100*	*-5*	*1.0-1.0*	*A+B: –*
Combined		*5.0-8.0*	*4.8-7.0*	*-2.0-0*	*72-100*	*88-98*	*-9-23*	*28-100*	*90-100*	*-8-66*	*0-3.2*	*A+B: 82-100*

[a]Outcomes are reported as mean ± SD (range minimum-maximum) unless otherwise indicated. Per category, overall variability and variability for proximal third, middle third and combined anterior cruciate ligament rupture location per outcome measure are summarized. Dashes denote that no data is available.
D, sum of FU score minus baseline score; 1I, one bundle, intact synovial sheath; 2R, 2 bundles, ruptured synovial sheath; ACLSR, anterior cruciate ligament suture repair; COL, bridging collagen scaffold; DA, dynamic augmented; DS, designer surgeon; FU, follow-up; HR, hardware removal; IKDC, International Knee Documentation Committee 2000; IKDCpe, IKDC physical examination score; IKDCs, IKDC subjective score; LM, Lachman at follow-up; N, nonaugmented; RAS, revision ACL surgery; RE#, rerupture; SA, static augmented; SG = subgroup.
[b]Minimum (mean or median) follow-up of 24 months.
[c]No statistically significant difference.
[d]Preoperative and not pre-injury.
[e]study reported results for NA and SA ACLSR; result for NA ACLSR were included in the NA ACLSR category.
[f]Statistical significance not reported.
[g]Median (interquartile range) (range: minimun-maximum).
[h]Statistically significant difference.

Comparative studies. Nine of the included studies were comparative.[1, 7, 15, 17, 27, 30, 44, 50, 55] Seven studies compared clinical outcomes of a contemporary ACLSR technique and ACLR (2 randomized controlled trials, both for DA ACLSR), of which 5 had a minimum (mean) follow-up of 2 years.[1, 7, 17, 27, 44, 50, 55] Furthermore, of these 7 studies, 5 evaluated failure, revision ACL surgery, complication, reoperation, and/or hardware removal rates; 4 evaluated patient-reported outcomes; and 4 evaluated knee laxity in terms of side-to-side difference in the Lachman test, including studies with a high level of evidence and CA scores. The majority of the studies comparing ACLSR and ACLR indicated no statistically significant difference between ACLSR and ACLR for these outcomes. [1, 7, 17, 27, 44, 50, 55] Only Gagliardi et al [17] observed a statistically significant higher failure rate for SA ACLSR, and Bieri et al[7] found a statistically significant higher hardware removal rate for DA ACLSR compared with ACLR. However, both had a low level of evidence and met only 50% and 64% of the CA criteria, respectively.

One study compared clinical outcomes of SA versus NA ACLSR techniques and reported no statistically significant differences at follow-up.[30] Another compared clinical outcomes of DA ACLSR for middle third ACL ruptures with and without the addition of a bridging collagen scaffold and found a statistically significant reduction of the failure rate with this addition.[15] None of the included studies compared ACLSR to conservative treatment.

DISCUSSION

The most important findings of this review are that, overall, there is high heterogeneity in study characteristics and a high risk of bias, as well as low levels of evidence and low-quality evidence, among the included studies evaluating contemporary ACLSR techniques. Regarding overall reported outcomes, there is high variability in failure rates within all ACLSR categories (NA, 0-25%; SA, 0-49%; DA, 0-27%), and rates for revision ACL surgery, complications and reoperations tended to be higher in the DA ACLSR category (0-20%, 2-61% and 2-33% respectively) than in the NA and SA ACLSR categories (0-8%, 0-0% and 0-15%; 0-7%, 0-2% and 0-10%).

Regarding reported outcomes with respect to ACL rupture location, only the SA and DA ACLSR category could be compared. Failure rates were higher in the proximal ACL rupture groups. Conversely, in DA ACLSR, rates for other complications are higher (and alike) in the middle third and combined ACL rupture group; in SA ACLSR, among the ACL rupture location groups, this was alike, and the variation in (and maximum of) reported rates

was lower compared to DA ACLSR. All in all, these findings make it difficult to interpret differences in clinical outcomes between ACLSR categories and ACL rupture locations.

Importantly, in several historical ACL suture repair series good short-term outcome was reported to deteriorate at mid-term follow-up.[16, 31, 40, 52, 53] In the present study, no papers of high quality and level of evidence with long-term follow-up were identified. However, with advancements in arthroscopic surgical techniques (instead of large arthrotomies), addition of small diameter (instead of no or larger-diameter) braid augmentation, addition of biological stimuli and postoperative rehabilitation protocols focusing on early functional recovery (instead of plaster cast immobilization for several weeks), better results for contemporary ACLSR might be expected. Indeed, contrary to several historical randomized clinical trials that reported superior outcome of ACLR over ACLSR, the majority of the comparative papers included in the present study, including those of high quality and level of evidence, indicated no statistically significant differences for complications, knee laxity and knee function, and/or patient-reported outcomes between all contemporary ACLSR technique and the current surgical gold standard, ACLR.[1, 7, 14, 18, 27, 44, 50, 55] Nevertheless, although ACLSR with modern techniques holds some promise, no meaningful conclusions can be made given the very poor quality of heterogeneous evidence overall. Strikingly, nearly half the studies had inadequate statistical analysis, because (1) the statistical test did not match the research questions, (2) the statistical test was not valid in origin (ie, paired tests for unrelated samples), (3) the statistical test was not present or was limited in the execution (ie, descriptive instead of statistical analysis in larger sample sizes), or (4) *P* values were presented without any information regarding the underlying type of statistical tests.

In contrast to the present findings, in a recently published systematic review, Van der List et al found much lower failure rates of 7-11% across all ACLSR categories. However, only studies evaluating (mainly) proximal ACL ruptures were included.[57] Ruptures located in the proximal third of the ACL are proposed to have the best healing potential.[35, 52, 56, 58] In the present review, contrary to those in the NA and SA ACLSR categories, the majority of the studies in the DA ACLSR category evaluated combined (or middle third) ACL ruptures, which could therefore have negatively influenced failure and other complication rates in DA ACLSR. On the other hand, a vast reduction in failure rate as well as other complication rates was observed after the addition of a bridging collagen scaffold to middle third ruptures in DA ACLSR.[15] The positive effect of a bridging collagen scaffold on ACL healing in SA ACLSR has already been extensively demonstrated in animal model studies.[49] Therefore, this might

improve results for ACLSR in both middle and proximal third ACL ruptures, irrespective of the ACLSR technique used. However, further studies to assess this are needed.

In contrast to the results of 2 previous systematic reviews that included mostly historical ACLSR series and given the heterogeneity and relatively low level of evidence and high risk of bias, the results of the present review do not support the superiority of ACLSR in proximal ACL ruptures over combined ACL ruptures in the contemporary ACLSR literature.[56, 58]

Studies in the DA ACLSR category showed a higher hardware removal rate than the NA and SA ACLSR categories. In the studies in this review, DA ACLSR was performed solely with a dynamic intraligamentary stabilization technique (Ligamys; Mathys Medical). The higher implant removal rate is probably due to the larger size of the tibial Ligamys implant (length 30 mm; diameter 10 mm), as compared to the smaller sized bone-anchors and/or cortical buttons used in NA and SA ACLSR techniques. Importantly, for DA ACLSR, some studies indicated that hardware was removed at patients' request and not only for medical reasons, probably resulting in an overestimation of reported hardware removal rates.[3, 13, 20, 24, 27, 33, 34, 47] Furthermore, a smaller tibial implant size might reduce the necessity for hardware removal in DA ACLSR in the near future.[21] Of note is that hardware removal did not appear to negatively influence knee laxity, and tibial bone loss after removal of the tibial implant did not seem to interfere with revision ACL surgery.[19, 22, 27] It is recommended that future research differentiate between hardware removal for medical and non-medical reasons.

With regard to patient-reported outcomes in ACLSR, the findings in the present review showed limited improvement or even a decrease of scores from baseline to follow-up of several commonly used patient-reported outcome measures, supporting the findings of Nwchukwu et al.[45] Importantly, overall scores at follow-up were high, and other than what is common in research for ACLR, the majority of studies included in the present review provided patient-reported outcomes for the preinjury instead of the preoperative state of the knee, which might explain this phenomenon.[27] Therefore, care should be taken in interpreting these findings when comparing differences in baseline and follow-up scores between studies presenting results for ACLSR and ACLR.

Limitations

This review has limitations that must be addressed. First, the high heterogeneity in study characteristics and reported outcome measures as well as in the overall low level and

quality of evidence among the included studies made pooling of data unreliable, so no meta-analyses were performed.

Second, this systematic review included more recent studies and more studies with a higher level of evidence compared to previous systematic reviews, underlining that ACLSR seems to be a rapidly developing field.[45, 54, 57] Therefore, studies currently under review or new studies published after the final search date of the present review could yield different insights regarding ≥ 1 of the described ACLSR categories. Furthermore, publication bias concerning studies rejected for publication and selection bias concerning included languages and databases in the literature search of the present systematic review may have led to underreporting on ≥ 1 of the described ACLSR categories.

Third, in this systematic review, no studies were found that compared contemporary ACLSR to conservative treatment. This might be due to selection bias caused by the employed key words and search strategy. However, no related studies were found after cross-checking the reference lists of the included articles, and to the authors knowledge no such comparative studies exist, nor have they been reported in previously published reviews concerning this subject.

All in all, despite these factors, this systematic review is a synthesis of the available evidence on the topic and can provide useful information to researchers and clinicians.

CONCLUSION

The current overall level and quality of evidence regarding contemporary ACLSR is poor, especially for SA ACLSR, and there is a lack of high-quality long-term outcome studies. This makes it difficult to interpret differences in clinical and patient-reported outcomes among ACLSR categories and ACL rupture locations. Although ACLSR with modern techniques holds some promise, it is difficult to determine the current role of ACLSR in treatment for acute ACL ruptures. The addition of an ACL bridging collagen scaffold may improve future outcomes for all ACLSR categories.

Implications

This review highlights a need for high-quality research, with larger groups of patients, including randomized controlled trials comparing ACLSR to the current surgical gold standard, ACLR, and focusing on appropriate allocation concealment, blinding, and adequate data presentation, including the mean and standard deviation or 95% confidence intervals. New research should also focus on long-term outcomes based on a standardized

recommended set of valid and reliable outcome parameters, including failure rate (which may be defined as the absence of subjective instability, absence of objective laxity and restoration of the ACL's continuity). Studies should preferably report on ACL rupture characteristics (location, bundles, synovial sheath integrity). Furthermore, more insights into patient selection criteria are needed, including the role of an additional bridging collagen scaffold or other biologic stimuli to ACLSR that might improve outcome even further. Based on this, high-quality guidelines could be developed to help orthopedic surgeons establish the role of contemporary ACLSR in the treatment algorithm for patients with a ruptured ACL.

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CHAPTER 3

Dynamic augmentation restores anterior tibial translation in ACL suture repair: a biomechanical comparison of non-, static and dynamic augmentation techniques

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ABSTRACT

Purpose: There is a lack of objective evidence investigating how previous non-augmented ACL suture repair techniques and contemporary augmentation techniques in ACL suture repair restrain anterior tibial translation (ATT) across the arc of flexion, and after cyclic loading of the knee. The purpose of this work was to test the null-hypotheses that there would be no statistically significant difference in ATT after non-, static- and dynamic-augmented ACL suture repair, and they will not restore ATT to normal values across the arc of flexion of the knee after cyclic loading.

Methods: Eleven human cadaveric knees were mounted in a test rig, and knee kinematics from 0° to 90° of flexion were recorded by use of an optical tracking system. Measurements were recorded without load and with 89-N tibial anterior force. The knees were tested in the following states: ACL-intact, ACL-deficient, non-augmented suture repair, static tape augmentation and dynamic augmentation after 10 and 300 loading cycles.

Results: Only static tape augmentation and dynamic augmentation restored ATT to values similar to the ACL-intact state directly postoperation, and maintained this after cyclic loading. However, contrary to dynamic augmentation, the ATT after static tape augmentation failed to remain statistically less than for the ACL-deficient state after cyclic loading. Moreover, after cyclic loading, ATT was significantly less with dynamic augmentation when compared to static tape augmentation.

Conclusion: In contrast to non-augmented ACL suture repair and static tape augmentation, only dynamic augmentation resulted in restoration of ATT values similar to the ACL-intact knee and decreased ATT values when compared to the ACL-deficient knee immediately post-operation and also after cyclic loading, across the arc of flexion, thus allowing the null hypotheses to be rejected. This may assist healing of the ruptured ACL. Therefore, this study would support further clinical evaluation of dynamic augmentation of ACL repair.

INTRODUCTION

Interest in primary repair of acute ruptures of the ACL has reawakened in the last decade as more insights on biology and biomechanics of the ruptured ACL have emerged [6, 16, 29, 36, 37]. Contemporary ACL suture repair has yielded good histological and biomechanical results in porcine and ovine animal model studies [18, 31, 38] and promising short- to midterm results in prospective clinical series [1, 2, 4, 6, 13, 22, 23, 30, 33].

In contrast to previous procedures (Figure 1), contemporary ACL suture repairs may be augmented with a suture or tape with bony fixation to approximate the ACL remnants, to help to maintain length, allow for early range of motion without compromising the repair site and promote healing [8-10, 17, 34]. However, in '*static'* augmentation, where the suture or tape is fixed to both the tibial and the femoral bone directly, anisometric placement and cyclic loading could lead to elongation of the repair and increase of anterior tibial translation (ATT) and therefore isometric femoral and tibial tunnel position is important [10, 17]. Unfortunately, in practice, isometric tunnel placement can most likely not be achieved (Figure 2) [17, 20, 40]. '*Dynamic'* augmentation may address the problems associated with anisometric tunnel placement and cyclic loading by attaching the suture or tape to an additional elastic link (a spring-in-screw mechanism) on the tibial side [17, 34], to allow length changes to occur during knee motion while maintaining reduction of ATT (Figure 3).

Although augmented suture repairs of the ruptured ACL are performed on patients today, there is a lack of objective evidence investigating how contemporary augmentation techniques in ACL suture repair affect ATT across the arc of flexion, and after cyclic loading of the knee (simulating postoperative rehabilitation), and how they relate to previous non-augmented repair techniques [1, 4, 6, 13, 19, 22, 23, 25, 28, 30, 33, 39].

Therefore, the purpose of this study was to gain insight into the biomechanical properties of contemporary static and dynamic augmentation techniques in ACL repair, and to put them in historical perspective by comparing them to a non-augmented ACL suture repair technique that was frequently used late in the last century, when suture repair of the ruptured ACL was abandoned in favour of ACL reconstruction. The aim was to examine the following null-hypotheses: there would be no statistically significant difference in ATT after non-augmented sutured, static augmented and dynamic augmented ACL repair, and they will not restore ATT to normal values in all flexion angles of the knee after cyclic loading (simulating postoperative rehabilitation).

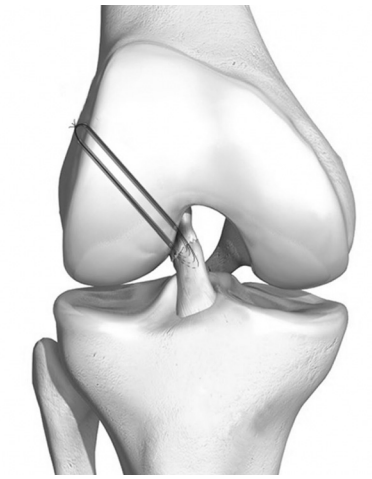

Figure 1. Non-augmented suture repair of the ruptured ACL. Looping sutures through the tibial stump of the ruptured ACL, led through two femoral tunnels (in the posterolateral and anteromedial attachment of the ACL) and knotted over the lateral femoral cortex.

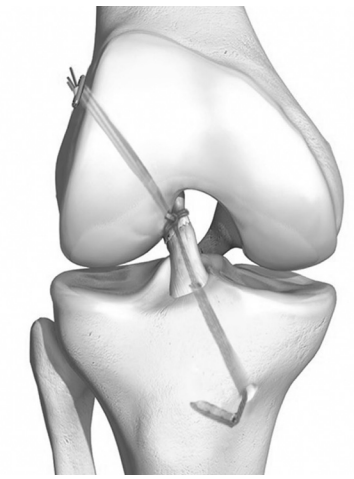

Figure 2. Static augmentation of the ruptured ACL. ACL suture repair augmented with intraligamentary tape with cortical interference screw fixation on the tibial side and variable loop length cortical button fixation device on the femoral side.

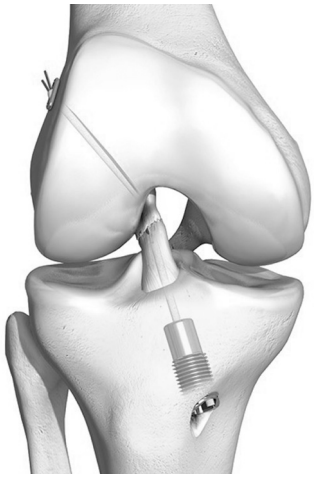

Figure 3. Dynamic augmentation of the ruptured ACL. ACL suture repair augmented with intraligamentary braid with cortical button fixation on the femoral side and additional elastic link (a spring-in-screw mechanism) on the tibial side.

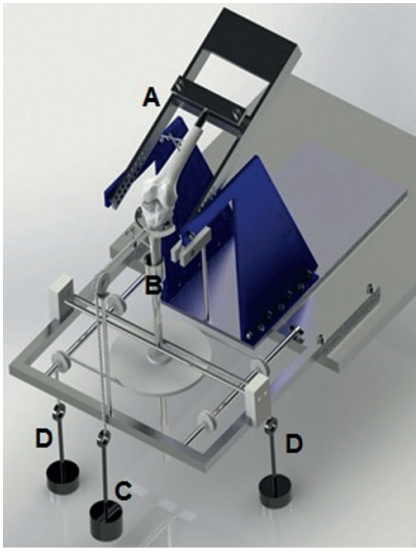

Figure 4. Test rig used for the study. The specimen position was adjusted to approximately align knee and rig flexion-extension axes. (A) Manual passive flexion-extension movements were applied to the femur; the motion of the hanging tibia (B) was otherwise unconstrained. The anterior (C) and posterior forces were applied with weights connected to the proximal tibia by cables passed over pulleys, via two semicircular hoops which were mounted on a Steinmann pin drilled mediolaterally across the tibia pendicular to the shaft at the level of the tibial tuberosity. Internal and external rotation torque was applied with weights (D) connected via a pulley and string system to opposite poles of a 200-mm polyethylene disc secured at the end of the tibial intramedullary rod (reprinted with permission of Stephen et al. [35]).

MATERIALS AND METHODS

Specimen preparation, optical tracking, testing protocol and data analysis were performed as described extensively by Stephen et al. [35].

Specimen Preparation

Fourteen fresh-frozen cadaveric knee specimens were obtained from a tissue bank. Two specimens were used to develop the testing protocol, and the data of one specimen was corrupted and could not be analysed. The remaining 11 knees were included for final data analysis (mean age 49 (range 28-59), 8 right sided, 3 left sided, 6 male, 5 female). The specimens were stored at –20°C and thawed for 24 hours before use. After preparation of the specimens, leaving all soft tissues except the skin and subcutaneous layer intact, the femur and tibia were cut and cemented to axially aligned rods. After preparation, the femoral rod was secured in a rig allowing manual passive knee flexion-extension from 0° to 90° by moving the femur with the unconstrained tibia hanging vertically (Figure 4). Anterior and posterior drawer forces without inducing rotational torque or inhibiting natural coupled tibial rotation, and rotational torques, could be imposed on the specimens as shown in Figure 4. All surgical procedures and testing took place on the same day without removing the specimen from the test rig.

Optical Tracking

Tibiofemoral joint kinematics were measured by use of a Polaris optical tracking system (NDI–Northern Digital Inc.) with passive digitized sets of Brainlab reflective markers (Brainlab) mounted securely onto the tibia and femur. Kinematic data were processed by use of Visual3D (C-Motion Inc.). Zero-degrees knee flexion was defined when the tibial and femoral rods were parallel in the sagittal plane. Anterior-posterior translation was calculated as the perpendicular distance from the midpoint of the femoral epicondylar axis to the tibial coronal reference plane [3, 15, 21, 35]. The tracking system is known to have a translational accuracy of 0.1mm, and this test method has been used previously[3, 15, 21, 35]. The intact knee at full extension (0° of flexion) was taken to be 0 mm translation and 0° rotation, and all measurements were normalized to this. The motions described are tibial motion in relation to the femur.

Surgical Procedures

All surgical procedures were performed by the surgeon author (R.H.), who has considerable experience in ACL reconstruction surgery. After mounting the knee in the kinematic test rig

the integrity of the ligaments, menisci and joint surfaces were checked by manual testing of laxities, and with standard arthroscopy through anteromedial and anterolateral portals. Laxity tests were performed with the ACL intact knee. Arthroscopically, the native ACL was transected close to the femoral attachment with a beaver knife, and left in situ. The laxity tests were repeated with the ACL deficient knee.

The knee was prepared arthroscopically so three suture techniques could be performed. To replicate in vivo circumstances the femoral and tibial tunnels were created with the transected ACL in situ. Two 2.4 mm diameter femoral tunnels were created from the femoral ACL attachment to the lateral distal femoral cortex with a drill tip guide pin with eyelet, which was placed through an accessory anteromedial portal, just superior to the tibial plateau and medial meniscus and just anterior to the medial femoral condyle, with the knee in 120 degrees of flexion. One guide pin was positioned in the "isometric point"[11] in the "high" and "deep" part of the femoral anteromedial bundle attachment. Since this "isometric point" was not visible with the ruptured ACL in situ, an offset guide was used to replicate in vivo circumstances. The other guide pin was positioned in the femoral posterolateral bundle attachment freehand. An incision was made to expose the lateral femoral cortex in the trajectory of the guide pins, to allow cortical fixation of the buttons and sutures. Both guide pins were removed and shuttle wires were pulled through the tunnels.

One 2.4 mm diameter tibial tunnel of at least 50mm length was created with a drill tip guide pin using an aiming device from the anteromedial aspect of the tibial metaphysis to the "isometric point" in the anterior part of the tibial attachment of the remaining ACL stump [11]. A shuttle wire was pulled through the tibial tunnel.

Suture repair of the ruptured ACL. Four Ethibond-0 sutures (Ethicon, Somerville, NJ, USA) were passed through the distal part of the sectioned ACL, in an anterior to posterior direction, starting near the attached base and progressing toward the torn end (the Marshall technique) [26, 27, 32]. The suture ends were grouped together into 2 groups, keeping the anteriorly and posteriorly exiting sutures separate. The posterior suture group was pulled through the posterolateral femoral tunnel, and the anterior suture group was pulled through the "isometric" anteromedial femoral tunnel with shuttle wires. The knee was placed in 20 degrees of flexion, with a posterior translation force of 80-N imposed on the tibia by the kinematics test rig [34]. The individual suture ends were pulled tight to eliminate any slack, and the 2 groups of sutures were tied down as one unit over the cortical bone surface

between the two femoral tunnels on the lateral aspect of the distal femur. The laxity tests were repeated, and the ACL was resected and the Marshall sutures were removed.

Static tape augmentation of the ruptured ACL. New shuttle wires were placed in the tibial and "isometric" anteromedial femoral tunnels. A cortical button suspension with adjustable loop length (Tightrope™ RT, Arthrex, Naples, Florida, USA) was loaded with a double loop tape (FiberTape™ 2mm, Arthrex, Naples, Florida, USA), and pulled through the tibial and femoral tunnel with shuttle wires, and it was verified that the button was fixed behind the lateral femoral cortex[12, 39]. The loop of the suspensory fixation was shortened until the tape was pulled approximately 20mm inside the femoral tunnel. A 3.5mm bone socket was created 10mm distal to the tibial tunnel in the anteromedial aspect of the tibia. The socket was tapped to 4.75mm. The tibial ends of the double loop tape were loaded into the eyelet at the tip of a screwdriver (SwiveLock™, Arthrex, Naples, Florida, USA). The knee was placed in 0 degrees of flexion, with a posterior translation force of 80N imposed on the proximal tibia by the kinematics test rig [25, 34]. While pulling the tape with manual tension in the direction of the tibial tunnel, the tip of the loaded screwdriver was placed in the opening of the tibial socket and the distal ends of the tape were pulled parallel to the screwdriver. The tape was marked at the level of the depth mark on the screwdriver. With the tip of the screwdriver repositioned to the level of the marking on the tape the SwiveLock™ was pushed inside the 3.5mm tibial socket manually until the depth mark on the screwdriver lined up with the tibial cortex. The tape was then secured in the tibial socket with the SwiveLock™ PEEK bone anchor interference screw (Figure 2). The laxity tests were repeated. After the laxity tests, if this procedure was not randomized to be the last procedure, the tape was removed.

Dynamic augmentation of the ruptured ACL. A 2.4mm guide pin was positioned in the 2.4mm tibial tunnel. An outside-in tibial socket 30mm long and 10mm in diameter was reamed over the guide pin with a cannulated drill with depth limitation. A Ligamys™ Monobloc second generation fixation device (Mathys, Betlach, Switzerland) was screwed inside the tibial bone tunnel over the guide pin, until it lined up with the tibial cortex. The guide pin was removed and a shuttle wire was led through the tibial and "isometric" anteromedial femoral tunnels. A Ligamys™ braid was pulled distally through the femoral and tibial tunnels with the shuttle wire, and it was verified that the proximal fixation button abutted the lateral femoral cortex. The knee was placed in 0 degrees of flexion [34]. With the tensioner, the braid was tensioned to maximal manual load and released, after which it was tensioned again to 80-N (Mathys Surgical Instructions) [34]. A clamping cone was fixed into the Ligamys™ Monobloc with a torque screwdriver. The laxity tests were repeated.

The clamping cone was removed from the Monobloc to release the tension on the Ligamys™ braid, the same tensioning procedure was repeated with 60-N (to match the tension used in the other suturing methods) [34] and the laxity tests were repeated.

After the laxity tests, if this procedure was not randomized to be the last procedure, the Ligamys™ Monobloc was removed, a greased 2.4mm drill pin was placed in the tibial tunnel, the tibial socket was filled with polyester car body filler and the drill pin was removed after the filler had hardened.

Testing Protocol

The 6 degrees of freedom data of the position of the tibia with respect to the femur were recorded with no external loads applied to the tibia, only the weight of the hanging tibia and attached rod, which remained constant throughout testing. The kinematic data were also recorded with the following loads applied in randomized order: 89-N tibial anterior drawer force, 89-N tibial posterior drawer force, 5-Nm tibial internal rotation torque, 5-Nm tibial external rotation torque, and a combined 89-N tibial anterior drawer force and 5-Nm tibial internal rotation torque to simulate the pivot shift laxity [24].

This test protocol of 6 loading conditions was repeated with the knee in 10 states: ACL intact and ACL sectioned state, as well as ACL suture repair, static tape augmentation and dynamic augmentation with 80-N and with 60-N pretension state after 10 and 300 cycles of flexion and extension between 0 and 90 degrees.

During development of the protocol, testing of the non-augmented ACL repair led to pull-out of the sutures, weakening the ACL stump. Therefore, after having tested the intact state and sectioned state, the repaired state of the ACL with the suture technique was tested first, after which the static tape augmentation and dynamic augmentation techniques were tested in randomized order per specimen. Testing of the dynamic augmentation with 80-N pretension always preceded testing with 60-N pretension.

During each test, 3 cycles of knee flexion-extension between 0° and 90° were repeated manually to gather the data.

The local Institutional Review Board (IRB: Imperial College Healthcare Tissue Bank, London, UK; IRB Nr. R17007) approved this study.

Statistical Analysis

The mean tibial translations and rotations were calculated at 10° intervals from 0° to 90° of flexion. The coordinate system was defined so that ATT and external rotation were taken to be positive. Visual3D motion data were processed using custom-written Matlab scripts (The MathWorks Inc.).

A power calculation using G*Power software *a priori* [7], based on prior work that used the same optical tracking system [14] determined that a sample size of 11 would allow identification of changes of translation and rotation of 0.8 mm and 0.9°, respectively, with 80% power and 95% confidence. Dependent variables were anterior and posterior translation, internal and external rotation and combined anterior translation and internal rotation laxities.

Data were analysed in SPSS (version 22.0; IBM Corp). The primary factors investigated were the 10 knee states and 7 flexion angles (0°-10°-20°-30°-40°-60°-90°). A mixed-model analysis for repeated measures was performed to study both the effect of the different flexion arcs and the effect of the different knee states on the dependent variables. Post hoc SIDAK tests were applied when differences between knee states or flexion arcs were found in order to investigate which knee states or flexion arcs differed while controlling for multiple comparisons. Furthermore, the interaction effect of knee state and flexion arc on the dependent variables was studied. Level of significance was set at $p<0.05$.

RESULTS

Mean ATT across the arc of flexion for different states of the knee is presented in Table 1. Rather than present normal laxity data, Table 1 and the following sections display movements away from the free-hanging position of the tibia (neutral loading) when the ACL was intact, which has greater clarity regarding residual laxities after different stages of the experiment.

Anterior Drawer

While applying 89-N of anterior force sectioning of the native ACL resulted in a significant increase of ATT ($p=0.000$; Table 1).

Directly post-operation (10 cycles), with non-augmented suture repair of the ACL and static tape and dynamic augmentation (for both 80 and 60-N pretensioning) the ATT was not significantly different than in the intact knee. However, with non-augmented suture repair

of the ACL the ATT was not significantly different than the ACL-deficient knee either, while with static tape (p=0.011) and dynamic augmentation (for both 80 and 60-N pretensioning; p=0.000) the ATT was significantly less than the ACL-deficient knee (Figures 5, 6, 7 and 8 respectively).

After 300 movement cycles, with non-augmented suture repair of the ACL the ATT was significantly greater than the intact knee (p=0.000) and was not significantly different to the ACL-deficient state. With static tape and dynamic augmentation, the ATT was not significantly greater than the intact knee. However, with static tape augmentation the ATT was not significantly different to the ACL-deficient state either, while with dynamic augmentation the ATT remained significantly less than the ACL-deficient state (p=0.000; Figures 5, 6, 7 and 8 respectively).

Although cyclic loading tended to cause the ATT to increase, it did not cause a significant increase in laxity for any of the repairs as compared to directly postoperation. When compared to non-augmented suture repair of the ACL, cyclic loading did not lead to greater reduction of ATT with static tape augmentation, whereas dynamic augmentation did lead to a significant greater reduction of ATT (p=0.000; Figure 9). Furthermore, when compared to static tape augmentation, cyclic loading did not result in a significant reduction of ATT with dynamic augmentation with 60-N pretensioning, whereas in contrast, dynamic augmentation with 80-N pretensioning did result in significant reduction of ATT (p=0.028) (Figure 9).

Combined Anterior Drawer and Internal Rotation / Posterior Drawer / External Rotation / Internal Rotation

The state of the knee had no significant effect on ATT and internal rotation laxity under combined 89-N anterior force and 5-Nm of internal rotational torque. Similarly, the state of the knee had no significant effect on posterior tibial translation, external or internal rotation laxity after application of a 89-N posterior force and a 5-Nm of external or internal rotational torque respectively.

Table 1. Mean anterior tibial translation across the arc of flexion for different states of the knee.

Flexion Angle	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°
ACL Intact	3.7 (0.9)	4.5 (0.6)	4.8 (1.0)	4.9 (1.2)	5.0 (1.2)	5.1 (1.2)	4.9 (1.3)	4.6 (1.5)	4.0 (1.4)	3.4 (1.1)
ACL Deficiënt	7.4 (2.3)	8.1 (1.7)	8.5 (2.0)	8.8 (2.3)	8.8 (2.4)	8.6 (2.5)	8.0 (2.6)	7.2 (2.6)	6.4 (2.4)	5.8 (2.2)
Marshall 10	5.6 (2.4)	6.3 (2.4)	6.6 (2.6)	6.9 (2.6)	7.0 (2.6)	7.0 (2.5)	6.7 (2.53	6.2 (2.1)	5.5 2(.0)	4.9 (1.6)
Marshall 300	6.4 (2.3)	7.0 (2.2)	7.3 (2.5)	7.6 (2.6)	7.7 (2.5)	7.6 (2.4)	7.2 (2.4)	6.5 (2.3)	5.9 (2.2)	5.4 (1.9)
InternalBrace™ 10	4.9 (2.2)	5.3 (2.1)	5.4 (2.1)	5.6 (2.0)	5.8 (2.0)	5.8 (2.0)	5.6 (2.1)	5.3 2(.2)	4.7 (1.9)	4.3 (1.4)
InternalBrace™ 300	6.3 (2.3)	6.4 (2.5)	6.4 (2.4)	6.4 (2.1)	6.4 (1.9)	6.5 (1.8)	6.3 (1.9)	5.9 (2.0)	5.5 (1.9)	5.1 (1.6)
Ligamys™ 80N 10	3.9 (1.4)	3.9 (1.5)	3.9 (1.5)	3.9 (1.3)	4.0 (1.2)	4.1 (1.2)	4.0 (1.3)	3.6 (1.5)	3.0 (1.6)	2.5 (1.4)
Ligamys™ 80N 300	4.1 (1.5)	4.2 (1.6)	4.2 (1.8)	4.2 (1.6)	4.4 (1.4)	4.4 (1.3)	4.2 (1.5)	3.9 (1.6)	3.5 (1.6)	2.9 (1.4)
Ligamys™ 60N 10	4.0 (2.2)	4.3 (2.2)	4.3 (2.2)	4.5 (2.1)	4.7 (1.9)	4.7 (1.9)	4.6 (2.0)	4.1 (2.1)	3.4 (2.1)	3.2 (1.5)
Ligamys™ 60N 300	4.4 (2.3)	4.4 (2.2)	4.4 (2.1)	4.5 (1.9)	4.6 (1.8)	4.7 (1.9)	4.6 (2.0)	4.1 (2.1)	3.4 (2.1)	3.1 (1.6)

Mean anterior tibial translation (mm +/- standard deviation) of eleven knee specimens for all fourteen states, across the arc of flexion of the knee (per 10 degrees from 0-90 degrees of flexion).

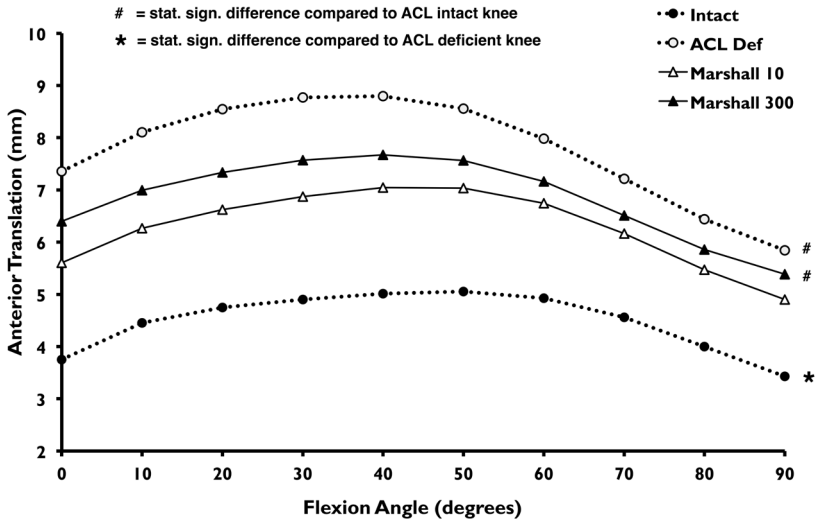

Figure 5. The difference in anterior tibial translation (mean; mm) across the range of knee flexion (degrees) from the neutral position of the tibia in the intact knee under 89-N anterior translation, for the intact knee, after ACL transection, and for the ACL sutured state after 10 and 300 movement cycles (n = 11).

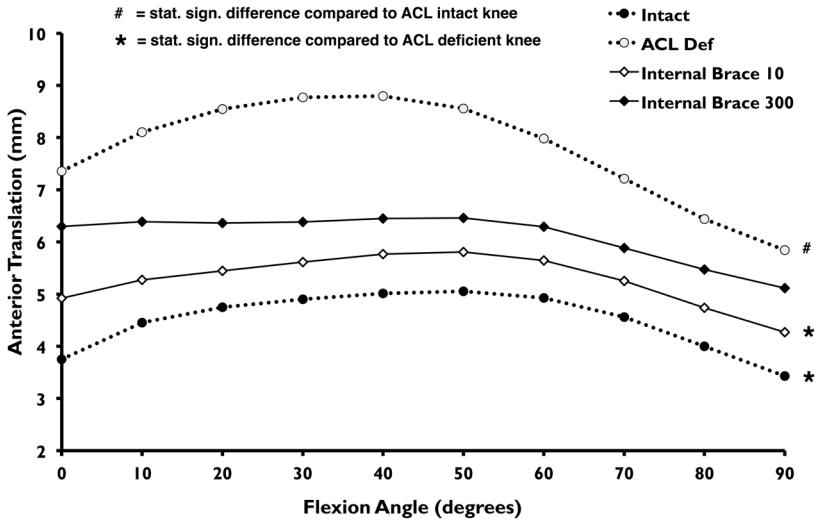

Figure 6. The difference in anterior tibial translation (mean; mm) across the range of knee flexion (degrees) from the neutral position of the tibia in the intact knee under 89-N anterior translation, for the intact knee, after ACL transection, and for the ACL with static tape augmentation after 10 and 300 movement cycles (n = 11).

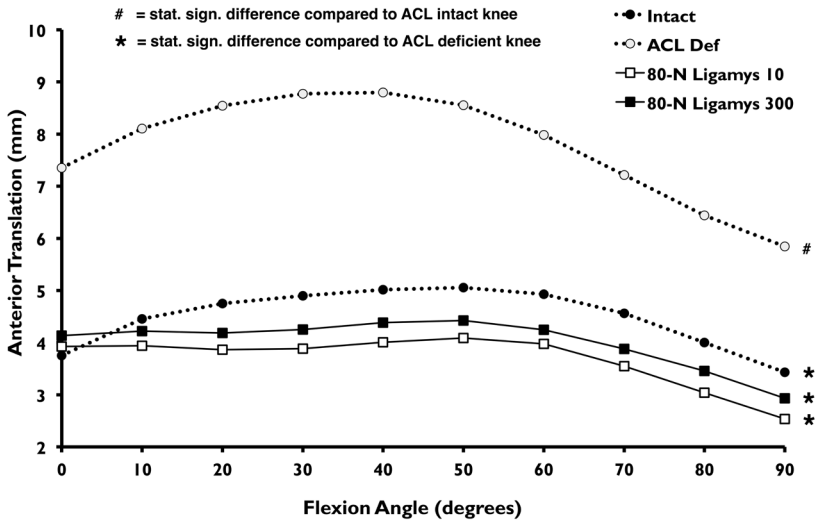

Figure 7. The difference in anterior tibial translation (mean; mm) across the range of knee flexion (degrees) from the neutral position of the tibia in the intact knee under 89-N anterior translation, for the intact knee, after ACL transection, and for the ACL with the dynamic augmentation device set to 80-N after 10 and 300 movement cycles (n = 11).

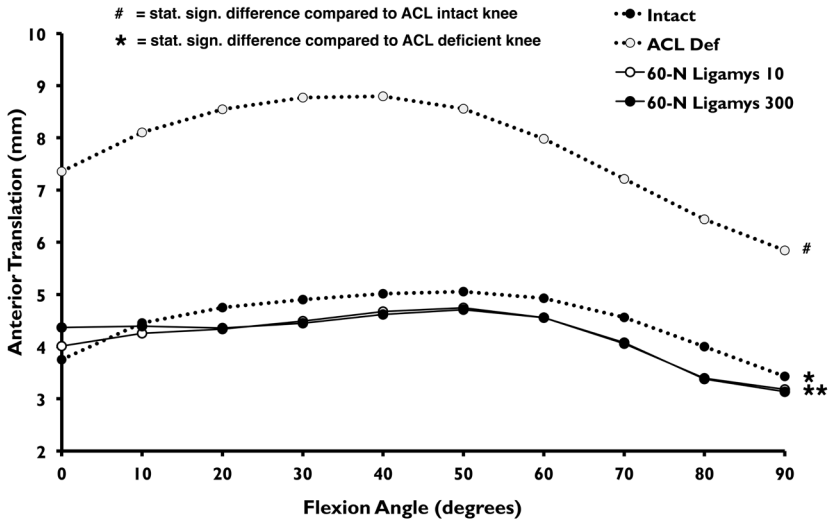

Figure 8. The difference in anterior tibial translation (mean; mm) across the range of knee flexion (degrees) from the neutral position of the tibia in the intact knee under 89-N anterior translation, for the intact knee, after ACL transection, and for the ACL with the dynamic augmentation device set to 60-N after 10 and 300 movement cycles (n = 11).

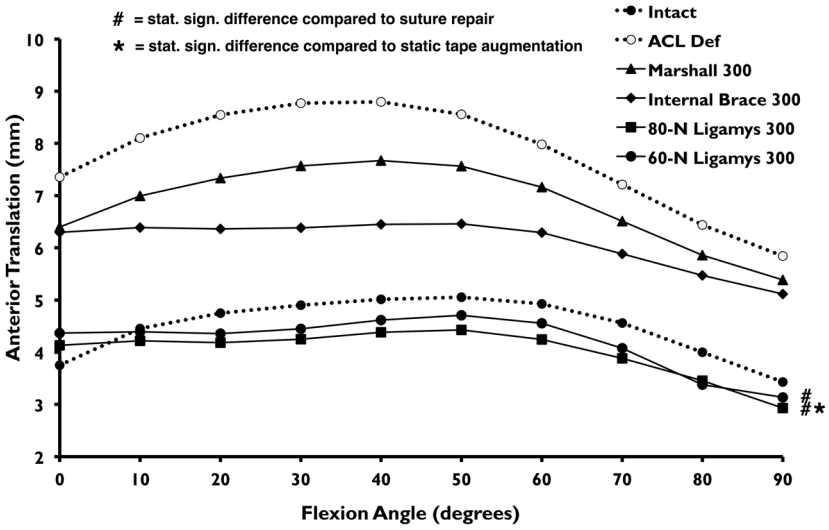

Figure 9. The difference in anterior tibial translation (mean; mm) across the range of knee flexion (degrees) from the neutral position of the tibia in the intact knee under 89-N anterior translation, for the intact knee, after ACL transection, and for the ACL sutured state, the ACL with static tape augmentation and the ACL with the dynamic augmentation device set to 80-N and 60-N after 300 movement cycles (n = 11).

DISCUSSION

The most important finding of this study is that, across the arc of flexion of the knee, only dynamic augmentation was able to restore ATT to values similar to the ACL-intact state and decrease ATT significantly compared to the ACL-deficient state directly postoperation, and to maintain this after cyclic loading, thus allowing the null hypotheses to be rejected.

Several biomechanical studies have shown that previously used ACL suture repair techniques may lead to higher than normal forces in the repair tissue, which could lead to repair stretching and failure [5], and did not restore normal ATT compared to the ACL-intact state [9, 10, 32], which is line with this study.

Contemporary augmentation techniques use strong, small diameter, non-resorbable braid. These cause little disruption of the ACL attachment and ACL tissue, and leave room for formation of hypertrophic scar tissue [10]. Contrary to earlier findings [5], more recent biomechanical studies in porcine [10], caprine [8, 9] and human [17, 34] knee specimens using

contemporary repair techniques have suggested that static tape and dynamic augmentation can restore ATT values to normal directly postoperation.

However, anisometric tunnel placement and cyclic loading may be of concern [10, 17]. In static tape augmentation, since there is no compensatory mechanism for length changes (other than limited elastic stretching/slackening of the tape), anisometric tunnel placement is associated with increased laxity both directly postoperation [10] and after cyclic loading [17], implying that anisometric tunnel placement can lead to elongation of a suture repair (and, consequently, the ACL) during early postoperative mobilisation [10, 17].

Dynamic augmentation addresses the concern about anisometric tunnel placement and cyclic loading in augmented ACL suture repair [17, 34]. It has been reported that dynamic augmentation with 85-N pretensioning restored laxity to normal directly postoperation and after cyclic loading, when tested in one flexion angle [17]. A comparison of dynamic stabilisation with 80-N versus 60-N pretensioning reported that 80-N pretensioning could restore ATT to normal across the arc of flexion directly postoperation [34].

This study supports these findings and found that dynamic augmentation restored ATT to normal values compared to the ACL-intact state, and decreased ATT significantly compared to the ACL-deficient state directly postoperation, and maintained that difference after cyclic loading, across the arc of flexion.

Although anisometric tunnel placement is addressed by dynamic augmentation, it does raise the concern of overconstraint or residual laxity depending on the amount of pretensioning. Although no statistical analysis was described, one biomechanical study seems to show overconstraint of the knee specimens compared to the ACL-intact state (mean -4.6mm) after 85-N pretensioning [17], while another reported normal ATT values with 80-N pretensioning and significant residual ATT with 60-N pretensioning [34]. Therefore, in this study, after dynamic augmentation, ATT was evaluated with 80-N as well as 60-N pretensioning. In contrast, this study found that dynamic augmentation yielded similar results with 60-N and 80-N pretensioning. The differences in findings between studies may partly have resulted from the force used during ATT tests: Schliemann et al. [34] used 134 N, Kohl et al [17] used 100 N, and the present study used 89 N.

Limitations

Besides the limitations that are inherent to all ex vivo testing some specific limitations apply to this study. The mean age of the specimens tested was higher than the typical age of the patient with this type of injury, despite efforts to source younger specimens. The results are only valid close to time zero, and it is not known how biological healing affects the repair over time, requiring further in vivo studies. Biomechanical testing may degrade the biomechanical properties of the ACL stump. Therefore, the non-augmented ACL suture repair was performed first, and the order of testing was thereafter randomized between static and dynamic augmentation.

It should be noted that the non-augmented ACL suture repair did reduce ATT so that it was not significantly increased compared to the ACL-intact state directly postoperative, although there was a significant increase in ATT after cyclic loading. Therefore, although this was not evaluated in this study, adding an ACL suture repair might improve the results of static tape augmentation and might also benefit a dynamic augmentation by helping to maintain apposition of the healing tissue. To establish healing of the ruptured ACL in vivo, adding suture repair to static or dynamic augmentation seems warranted.

The clinical relevance of this study is that it suggests that dynamic augmentation (Ligamys™) with 80-N pretensioning can control ATT laxity directly postoperation and can maintain this after short-term cyclic loading, which may assist healing of the ruptured ACL. Therefore, this study would support further clinical evaluation of dynamic augmentation of ACL repair.

CONCLUSION

The results of this cadaveric study have shown that, in contrast to non-augmented ACL suture repair and static tape augmentation, dynamic augmentation with 80-N pretensioning resulted in restoration of ATT values similar to the ACL-intact knee and decreased ATT values when compared to the ACL-deficient knee immediately post-operation and also after cyclic loading, across the arc of flexion.

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CHAPTER 4

Isometric placement of the augmentation braid is not attained reliably in contemporary ACL suture repair

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ABSTRACT

Background: To assess if during arthroscopic braid-augmented ACL suture repair (ACLSR), the actual positions of the augmentation braids' tunnels corresponded with the positions of their intended and targeted isometric points, and to test the hypothesis that there would be no dispersion in actual positions of the augmentation braids' tunnels compared to their intended and targeted isometric points.

Methods: In 12 human cadaveric knees, the positions of the augmentation braids' tunnels and their intended and targeted isometric points relative to a femoral and tibial grid were analyzed. Furthermore, vector length between these positions was calculated to assess the accuracy and precision of the augmentation braids' tunnel placement.

Results: There was dispersion for all of the augmentation braids' tunnel positions compared to their intended isometric points. The femoral and tibial vector lengths (mean ± SD (range)) were 2.9 ± 1.0 (1.1–4.1) and 7.1 ± 2.0 (3.2–9.8) mm respectively.

Conclusion: In augmented ACLSR, with the ruptured ACL in situ, there was dispersion of the positions of the actual small diameter femoral and tibial augmentation braids' tunnels away from their desired isometric points.

Clinical relevance: The extent of dispersion of the position of both the femoral and tibial tunnels away from their intended isometric positions may cause cyclic length changes with knee motion. An ACLSR with static braid augmentation will thus be vulnerable to cyclic stretching-out. The difficulty of obtaining an isometric tunnel combination for the small diameter augmentation braid may influence the clinician's choice between non-, static or dynamic augmented ACLSR techniques.

INTRODUCTION

In recent years there has been increasing interest in suture repair of the ruptured anterior cruciate ligament (ACL), and good short- to mid-term results have been reported[1-4]. Contemporary arthroscopic ACL suture repair techniques may use a strong, small diameter, non-resorbable augmentation braid positioned parallel to the sutured ACL to control anterior tibial translation across the arc of flexion and to protect the sutures from being pulled-out [5-10].

In contrast to the larger diameter native ACL or ACL reconstruction with a tendon graft, the small diameter augmentation braid yields a point-to-point like fixation. Therefore, since in static ACL suture repair the augmentation braid is fixed directly to both the femur and tibia, this implies the necessity for an isometric position of the augmentation braid, to prevent length change within the arc of flexion of the knee and resulting cyclic loading and elongation of the sutured ACL [7, 8, 10, 11]. However, in 'dynamic' augmented ACL suture repair the augmentation braid is fixed to the tibia indirectly through an additional elastic link consisting of a threaded sleeve housing with a preloaded spring to which the augmentation braid is fixed, which could compensate for the presence of cyclic length changes up to eight mm across the arc of flexion of the knee, precluding the need for a femoral and tibial isometric tunnel combination [8, 11, 12].

In a previous biomechanical comparison of three ACL suture repair techniques in human cadaveric knees, anterior tibial translation increased across the arc of flexion after cyclic loading with static augmentation but not with dynamic augmentation of the ruptured ACL [8]. This implies that the augmentation braid's tunnels were positioned anisometrically, but within the compensatory limits of the dynamic augmentation device. It is likely that this was caused by the fact that in ACL suture repair, the ruptured ends of the ACL are left in situ, impeding visibility of the native tibial and femoral ACL attachments.

Therefore, the purpose of this study was to assess whether the actual positions of the augmentation braids' tunnels obtained in the previous biomechanical study corresponded with the positions of their intended isometric points. The aim was to examine the null-hypothesis that there would be no dispersion in actual positions of the augmentation braids compared to the positions of their intended femoral and tibial isometric points.

MATERIALS AND METHODS

Specimen preparation and operative technique

For the previous biomechanical study, following Institutional Review Board (IRB: Imperial Colege Healthcare Tissue Bank, London, UK; IRB Nr. R17007) approval, 14 fresh-frozen human knee specimens were obtained from a tissue bank. With two specimens used to develop the testing protocol, 12 specimens were available for final data analysis (mean age 49 (range 28-59), eight right sided, four left sided, six male, six female). Preparation of the specimens and surgical procedure were described extensively by Hoogeslag et al. [8].

After mounting the knee specimen in a kinematic test rig, arthroscopy was performed through standard anteromedial and anterolateral portals. With a beaver knife the native ACL was cut near the femoral attachment.

The sectioned ACL was left in situ to replicate in vivo circumstances. The objective was to create an isometric tibial and femoral tunnel combination for the augmentation braid. In contrast to ACL reconstruction with a larger diameter tunnel for a tendon graft, the tunnels for the augmentation braid are small (points)[13]. Therefore, a single isometric tibial and femoral point combination was sought to position the augmentation braid's tunnels. Zavras et al. compared multiple suggested isometric point combinations, and reported the isometric point combination as described by Friederich et al. had a length change of close to zero mm across the arc of flexion, and that these points were positioned at the borders of the ACL's tibial and femoral attachments (Figure 1)[14-16]. Therefore, since in ACL suture repair the native ruptured ACL remains in situ, in the present study the tibial tunnel was targeted at the anterior border of the ACL attachment and the femoral tunnel was targeted at the proximal part of the femoral attachment along Blumensaat's line as described by Friederich et al.[14-16].

The tibial tunnel was created using an aiming device from the anteromedial aspect of the proximal tibia with a 2.4 millimetres (mm) diameter drill tip guide pin which was directed at the "isometric point" at the anterior border of the tibial attachment of the remaining ACL stump on the tibial plateau[14]. The femoral tunnel was created with a 2.4 mm diameter drill tip guide pin, which was placed through an accessory anteromedial portal, with the knee in 120 degrees of flexion. To replicate in vivo circumstances the guide pin was directed at the "isometric point" using an offset guide, since this femoral "isometric point" is not visible arthroscopically with the ruptured ACL in situ[14, 15]. In the context of the original biomechanical study, a second tunnel was created freehand in the femoral posterolateral ACL bundle attachment. For the current study, this tunnel was irrelevant and was ignored.

The surgeon author R.A.G.H. who, training knee-fellows and performing approximately 250-300 ACL reconstructions per year since 12 years, has considerable experience in ACL reconstruction surgery, performed all surgical procedures.

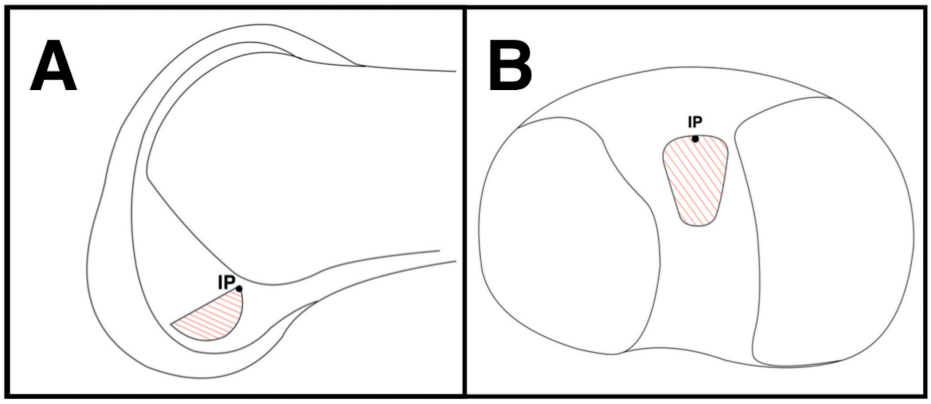

Figure 1. Schematic drawing of lateral view of distal femur (A) and axial view of tibial plateau (B), with isometric points (IP) according to Friederich et al. within the ACL attachments (red shaded) [14-16].

Specimen dissection

After drilling the tunnels and performing the original biomechanical experiment, the tibia and the femur were separated and all soft tissues were resected, including the remains of the ACL.

The femur was cut in the most proximal point of the notch in the sagittal plane and in the transverse plane so the medial femoral condyle could be removed [17-19]. With the medial femoral condyle repositioned to its original position, the femoral shaft was fixed to a stand with a clamp and the posterior and the distal condylar axes were aligned perpendicular to the floor with a carpenter's square. A digital photo camera was positioned and fixed perpendicular to the floor, with the lens's crosshair centred so that the contours of the condyles overlapped each other. This replicated a direct lateral view of the distal femoral condyles. After positioning the femur and the camera, the medial femoral condyle was removed to expose the medial side of the lateral femoral condyle with Blumensaat's line and the femoral tunnel, and a digital photograph was taken. A ruler was mounted in the field of view at the same height as the medial face of the lateral condyle, to allow measurements [18].

Subsequently, the tibial shaft was fixed to a stand with a clamp with the joint surface parallel to the floor. The digital photo camera was positioned perpendicular to the tibial joint surface and fixed with the lens's crosshair directed to the middle of the tibial plateau, and a digital photograph was taken with the ruler mounted at the level of the plateau.

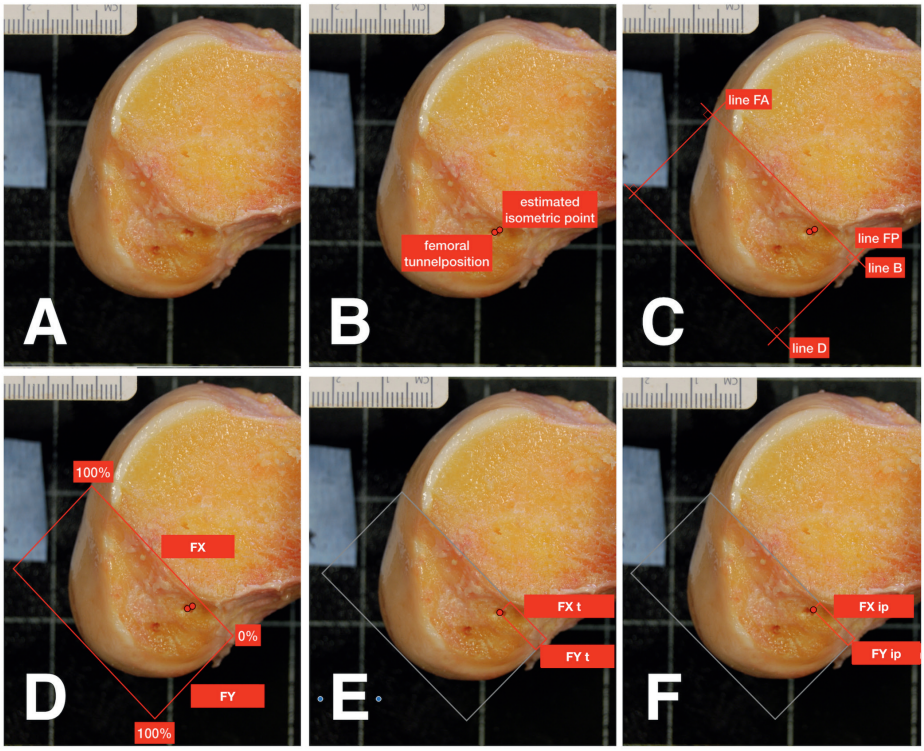

Figure 2. Femoral grid.

A: Lateral photograph of distal femur with medial femoral condyle removed, with the tunnel for the augmentation braid in medial wall of lateral femoral condyle.
B: Estimated position of the centre of the tunnel for the augmentation braid and its targeted isometric point.
C: A line along Blumensaat's line (line B, Blumensaat; x-axis of the femoral grid), two lines perpendicular to line B and intersecting line B at the level of the anterior (line FA, femoral anterior; y-axis of the femoral grid) and posterior (line FP, femoral posterior) border of the femoral condyle, and one line parallel to line B at the most distal aspect of the lateral femoral condyl (line D, distal).
D: Distance FX, the length of the femoral grid along the x-axis (line B from its intersection with line FP to line FA); and distance FY, the length of the femoral grid along the y-axis (line FP from its intersection with line B to line D).
E: Distance FX t, femoral x-axis tunnel: the distance of the centre of the femoral tunnel (to the y-axis) along the x-axis (in deep-shallow direction); and distance FY t, femoral y-axis tunnel: the distance of the centre of the femoral tunnel (to the x-axis) along the y-axis (in high-low direction).
F: Distance FX ip, femoral x-axis isometric point: the distance of the targeted isometric point (to the y-axis) along the x-axis (in deep-shallow direction); and distance FY ip, femoral y-axis isometric point: the distance of the centre of the targeted isometric point (to the x-axis) along the y-axis (in high-low direction).

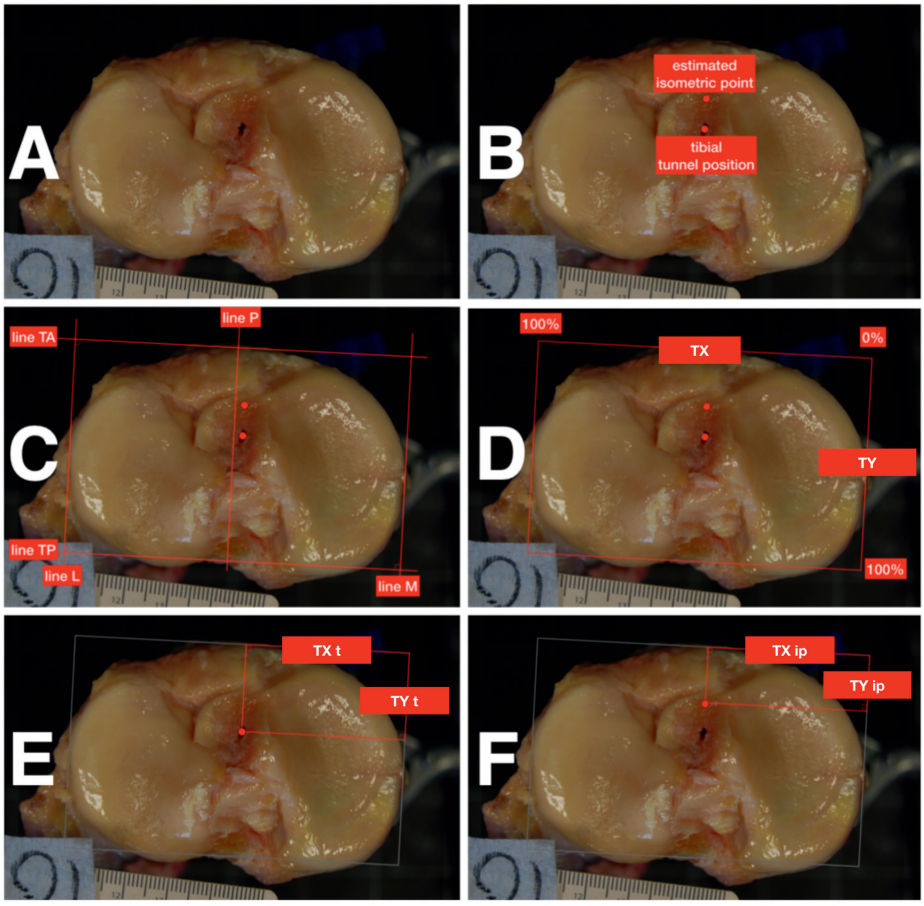

Figure 3. Tibial grid.

A: axial photograph of tibial plateau, with tunnel for the augmentation braid.
B: estimated position of the centre of the tunnel for the augmentation braid and its targeted isometric point.
C: a line perpendicular to the posterior condylar axis in the mid-sagittal plane (line P, perpendicular), two lines parallel to the posterior condylar axis, crossing the mid-sagittal line at the level of the anterior (line TA, tibial anterior; x-axis of the tibial grid) and posterior border (line TP, tibial posterior) of the tibia and two lines parallel to the mid-sagittal line placed at the medial (line M, medial; y-axis of the tibial grid) and lateral border (line L, lateral) of the tibia.
D: distance TX, the length of the tibial grid along the x-axis (line TA from its intersection with line M to line L) and distance TY, the length of the tibial grid along the y-axis (line S from its intersection with line TA to line TP)
E: distance TX t, tibial x-axis tunnel: the distance of the centre of the tunnel (to the y-axis) along the x-axis (in medial-lateral direction); and distance TY t, tibial y-axis tunnel: the distance of the centre of the tunnel (to the x-axis) along the y-axis (in anterior-posterior direction).
F: distance TX ip, tunnel x-axis isometric point: the distance of the targeted isometric point (to the y-axis) along the x-axis (in medial-lateral direction); and distance TY ip: the distance of the targeted isometric point (to the x-axis) along the y-axis (on the y-axis, in anterior-posterior direction).

Data collection

Measurements of the locations of the femoral tunnels and intended femoral isometric points were performed using the grid method described by Bernard et al. [20]. First, the ruler was calibrated.

Second, the position of the femoral tunnel and the intended isometric point were identified and marked.

Third, a digital grid was projected on the femoral photograph [20]. The deep-shallow direction was defined as the x-axis, and the high-low direction as the y-axis.

Fourth, two distances of the grid in mm were measured: the size of the lateral femoral condyle on the x-axis over Blumensaat's line (distance FX), and the maximum height of the intercondylar notch on the y-axis (distance FY).

Fifth, four distances of the actual tunnels and the intended isometric point position to the grid were measured: the distance of the centre of the small diameter femoral tunnel (distance FX t) and the intended isometric point (distance FX ip) on the x-axis to the most posterior contour of the lateral femoral condyle and the distance of the centre of the small diameter femoral tunnel (distance FY t) and the intended isometric point (distance FY ip) on the y-axis to Blumensaat's line (Figure 2).

Measurements of the location of the tibial tunnels and intended tibial isometric points were performed using the methods described by Amis et al. and Pietrini et al[21, 22]. First, the ruler was calibrated.

Second, the position of the tibial tunnel and the intended isometric point were identified and marked.

Third, a digital grid was also projected on the tibial photograph. The medial-lateral direction was defined as the x-axis, and the anterior-posterior direction as the y-axis.

Fourth, two distances of the grid were measured: the maximum coronal size of the tibia plateau on the x-axis (distance TX) and the mid-sagittal size of the tibia plateau in on the y-axis (distance TY).

Fifth, four distances of the actual tunnels and the intended isometric point position to the grid were measured: the distance of the tibial tunnel (distance TX t) and the intended isometric point (distance TX ip) on the x-axis to the most medial aspect the tibial plateau and the anterior-posterior distance of the tibial tunnel (distance TY t) and the intended isometric point (distance TY ip) on the y-axis to the most anterior aspect of the tibial plateau (Figure 3).

To assess the reproducibility of identification of the tunnel and isometric point positions, two experienced orthopaedic ACL surgeons R.A.G.H. and R.W.B. separately performed

the described measurements on two separate occasions at least six weeks apart, giving four repeats of each measurement.

Statistical analysis

Intra- and interobserver reliability were determined using the single-measure, two-way, absolute agreement intra class correlation coefficient (ICC) statistic.

Dispersion (the quantified variation) of the tunnel positions relative to their intended isometric point positions was investigated descriptively. First, per specimen, the mean values of the four quantitative measurements (mm) of the positions of the tunnels and their intended isometric points on the x- and y-axes were calculated, normalised to qualitative data (%) as a percentage of the grid to correct for the specimens' size differences, and visualized in an x-y diagram.

Second, per specimen, the differences between the positions of the tunnels and their intended isometric points on the x-and y-axes were calculated by subtraction ((value tunnel position minus value intended isometric point position) for both the quantitative (mm) and qualitative (%) data.

Third, per specimen, the two-dimensional vector lengths between the positions of the tunnels and their intended isometric points on the x-axis and y-axis combined were calculated with the Pythagorean theorem (square root (difference x-axis^2) + (difference y-axis^2)) for both the quantitative (mm) and qualitative (%) data, and the qualitative data (%) were visualized in an x-y diagram.

Fourth, to assess the accuracy of tunnel positioning, the mean value of the two-dimensional vector length (representing the mean difference (MD) between the position of each tunnel and its intended isometric point) was calculated, and to assess the precision of tunnel positioning, the standard deviation and the range of the vector length were calculated, for both the quantitative (mm) and qualitative (%) data.

All analyses were conducted in Keynote (Apple, Cupertino, USA), Excel (Microsoft, Redmond, USA) and SPSS 24 (IBM, Chicago, USA).

RESULTS

Reproducibility of identification of landmarks

Intra- and interobserver reliability were excellent for all measurements of the tibial and femoral actual tunnel positions, and their intended isometric point positions (>0.91), except for the ICC for intended femoral isometric point position on the y-axis (high-low direction: FY ip), which was good (>0.75) (Appendix A).

Dispersion

The mean values of the four repeat measurements of the quantitative (mm) and qualitative (%) positions of the actual tunnels and the intended isometric points per specimen relative to the x- and y-axes of the femoral and tibial grids are presented in Table 1 and Table 2 respectively. The values for all four measurements of the quantitative (mm) positions of the actual tunnels and the intended isometric points per specimen relative to the x- and y-axes of the femoral and tibial grids are presented in Appendices B and C respectively.

The visualisation of the mean qualitative (%) values of all four measurements of the positions of the tunnels and their intended isometric points on the x- and y-axes per pair is presented in x-y diagrams in Figures 4 and 5. These x-y diagrams show that there was dispersion of the tunnels away from their intended isometric points, especially on the femoral and the tibial y-axes (in high-low and in anterior-posterior direction respectively).

The quantitative (mm) and qualitative (%) difference between the position of the tunnel minus its intended isometric point on the x- and the y-axes and the two-dimensional vector lengths between the position of the tunnel and its intended isometric point per specimen, as well as the mean value of the vector length with standard deviation and range are presented in Tables 3 and 4, and shown in Figures 4 and 5. The quantitative femoral vector length was 2.9 $\pm$ 1.0(1.1-4.1) (mean $\pm$ SD (Range min-max)) mm, the qualitative femoral vector length was 9.3 $\pm$ 4.3 (6.2-18.5) %, the quantitative tibial vector length was 7.1 $\pm$ 2.0 (3.2-9.8) mm and the qualitative tibial vector length was 14.3 $\pm$ 4.3 (6.0-20.0) %.

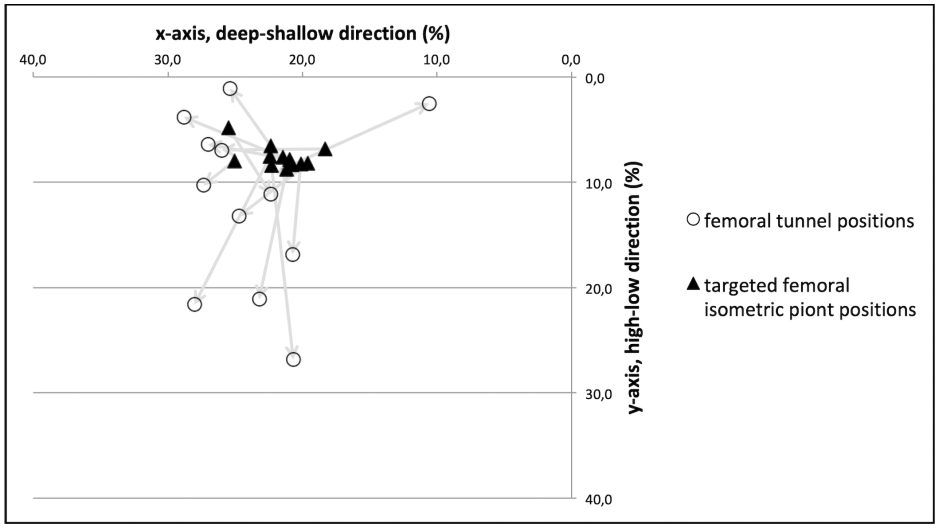

Figure 4: Femoral x-y diagram. Two-dimensional partial femoral grid illustrating qualitative (%) mean values of actual tunnel (circles) and their intended and targeted isometric tunnel positions (triangles) per specimen on the x-axis and the y-axis (in deep-shallow and high-low direction respectively), as well as the two-dimensional vector length representing the mean difference between the position of each actual tunnel and its intended and targeted isometric tunnel position.

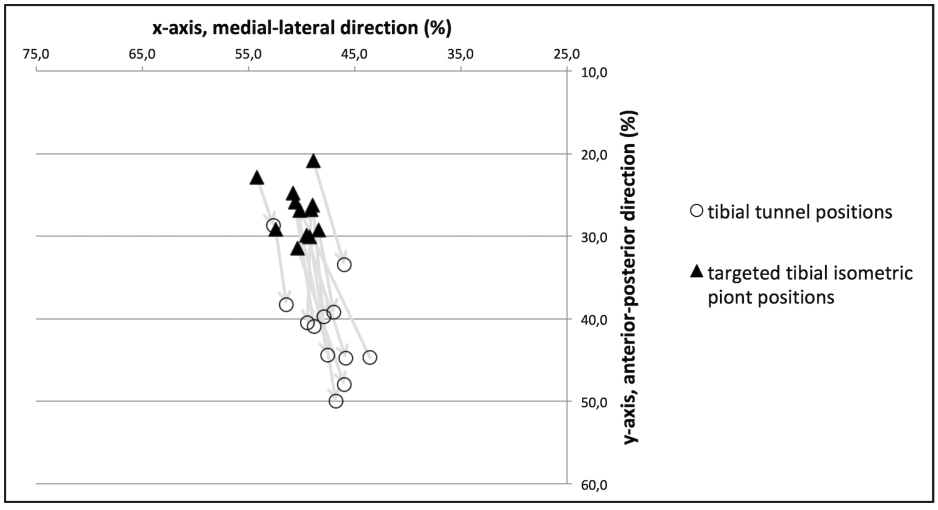

Figure 5: Tibial x-y diagram. Two-dimensional partial tibial grid illustrating mean values of actual tunnel (circles) and their intended and targeted isometric tunnel positions (triangles) per specimen on the x-axis and the y-axis (in medial-lateral and anterior-posterior direction respectively), as well as the two-dimensional vector length representing the mean difference between the position of each actual tunnel and its intended and targeted isometric tunnel position.

Table 1. The size of the femoral grid (mm) and the quantitative (mm) and qualitative (%) mean values of four repeat measurements of the positions of the actual femoral tunnels and their intended isometric point positions relative to the grid, per specimen.

specimen	FX	FX t mean / specimen		FX ip mean / specimen		FY	FY t mean / specimen		FY ip mean / specimen	
		mm	%	mm	%		mm	%	mm	%
3	45,1	10,5	23,2	9,5	21,2	24	5	21,1	2,1	8,8
4	47,8	13,8	28,8	10,3	21,5	23,3	0,9	3,8	1,8	7,6
5	38,5	4,1	10,6	8	20,8	20,6	0,5	2,5	1,7	8,4
6	48,3	12,3	25,4	10,8	22,4	22,7	0,2	1,1	1,5	6,5
7	43,3	9,7	22,4	11	25,5	23	2,6	11,1	1,1	4,8
8	41,3	10,8	26	7,6	18,3	21,7	1,5	6,9	1,5	6,8
9	41,1	10,2	24,7	8	19,6	22,8	3	13,2	1,9	8,2
10	45,8	12,4	27	9,6	21	22,2	1,4	6,4	1,7	7,8
11	44,3	12,4	28	9,9	22,4	23,1	5	21,6	1,7	7,6
12	41,2	8,5	20,7	9,2	22,3	23,3	6,2	26,8	2	8,4
13	42,6	11,7	27,4	10,7	25,1	20,9	2,1	10,3	1,7	8
14	44,6	9,2	20,7	9	20,1	24,3	4,1	16,8	2	8,3

FX = distance of line FX; FY = distance of line FY; FX t = distance of line FX t; FX ip = distance of line FX ip;; FY t = distance of line FY t; FY ip = distance of line FY ip. Measurement in millimetres unless otherwise indicated.

Table 2. The size of the tibial grid and the quantitative (mm) and qualitative (%) mean values of four repeat measurements of the positions of the actual tibial tunnels and their intended isometric point positions relative to the grid, per specimen.

specimen	TX	TX t mean / specimen		TX ip mean / specimen		TY	TY t mean / specimen		TY ip mean / specimen	
		mm	%	mm	%		mm	%	mm	%
3	69,6	30,3	43,5	34,9	50,2	46,9	21	44,7	12,6	26,9
4	78,2	41,2	52,7	42,4	54,2	51,7	14,8	28,7	11,8	22,9
5	68,4	33,9	49,5	33,6	49,1	47,7	19,3	40,5	12,8	26,8
6	79,1	37,2	47	38,3	48,4	54,1	21,2	39,3	15,8	29,3
7	72,7	37,4	51,4	38,1	52,4	49,1	18,8	38,3	14,3	29,2
8	69,9	32,7	46,8	34,4	49,3	48,2	24,1	50	14,5	30,1
9	70,4	32,4	46	35,5	50,4	47,8	22,9	48	15,1	31,5
10	77,2	37,7	48,8	39,2	50,8	49	20,1	41	12,2	24,8
11	73,5	34,9	47,6	37,2	50,6	48,2	21,4	44,4	12,5	25,9
12	68,6	31,4	45,8	33,9	49,5	46,3	20,7	44,8	13,8	29,9
13	73,6	35,3	47,9	36,1	49	49,3	19,6	39,7	13	26,3
14	73,3	33,7	46	35,8	48,9	51,2	17,1	33,4	10,7	20,9

TX = distance of line TX; TY = distance of line TY; TX t = distance of line TX t; TX ip = distance of line TX ip; TY t = distance of line TY t; TY ip = distance of line TY op. Measurement in millimetres unless otherwise indicated.

Table 3. The quantitative (mm) and qualitative (%) difference between the mean values of the actual position of the femoral tunnels and their intended isometric point positions per specimen, the two-dimensional vector length per specimen, and the mean value of vector with standard deviation (SD) and range.

specimen	femoral delta X		femoral delta Y		femoral 2D vector	
	mm	%	mm	%	mm	%
3	1	2,2	2,9	12,3	3,1	12,5
4	3,5	7,3	-0,9	-3,8	3,6	8,2
5	-3,9	-10,2	-1,2	-5,8	4,1	11,8
6	1,5	3,1	-1,2	-5,5	1,9	6,3
7	-1,3	-3	1,5	6,5	2	7,2
8	3,2	7,7	0	0,1	3,2	7,7
9	2,2	5,4	1,1	5	2,5	7,3
10	2,8	6	-0,3	-1,5	2,8	6,2
11	2,5	5,6	3,3	14,1	4,1	15,1
12	-0,7	-1,6	4,2	18,1	4,3	18,1
13	1	2,3	0,4	1,9	1,1	3
14	0,2	0,4	2,1	8,5	2,1	8,6
mean					2,9	9,3
SD					1	4,3
range					1.1-4.1	6,2-18,5

X=femoral x-axis (deep-shallow direction), Y = femoral y-axis (high-low direction), 2D = two-dimensional, mm = millimeter, % = percentage.

Table 4. The quantitative (mm) and qualitative (%) difference between the mean values of the actual position of the tibial tunnels and their intended isometric point positions per specimen, the two-dimensional vector length per specimen, and the mean value of vector with standard deviation (SD) and range.

specimen	tibial delta X		tibial delta Y		tibial 2D vector	
	mm	%	mm	%	mm	%
3	-4,6	-6,6	8,4	17,9	9,5	19,1
4	-1,2	-1,5	3	5,8	3,2	6
5	0,3	0,4	6,5	13,6	6,5	13,6
6	-1,1	-1,4	5,4	10	5,5	10,1
7	-0,7	-1	4,5	9,2	4,5	9,2
8	-1,7	-2,4	9,6	19,9	9,8	20
9	-3,1	-4,4	7,8	16,3	8,5	16,9
10	-1,5	-1,9	7,9	16,1	8,1	16,2
11	-2,3	-3,1	8,9	18,5	9,2	18,7
12	-2,5	-3,6	6,9	14,9	7,3	15,3
13	-0,8	-1,1	6,6	13,4	6,7	13,4
14	-2,1	-2,9	6,4	12,5	6,8	12,8
mean					7,1	14,3
SD					2	4,3
range					3.2-9.8	6,0-20,0

X=tibial x-axis (deep-shallow direction), Y = tibial y-axis (high-low direction), 2D = two-dimensional, mm = millimetre, % = percentage.

DISCUSSION

The most important result of the present study is that in a series of augmented ACL suture repairs, there was a dispersion (a quantified variation) of the actual positions of the tibial and femoral tunnels around their intended isometric points. On average, the femoral and tibial tunnels for the augmentation braid were 2.9mm (9.3%) and 7.1mm (14.3%) away, respectively, from the desired isometric targets.

Dispersion of the actual position of the tunnels compared to their intended isometric points would lead to anisometry of the augmentation braid in ACL suture repair. In a biomechanical study in the human cadaveric knee, Zavras et al. found that even the slightest misplacement of tunnels away from a small isometric area within the ACL's femoral attachment, corresponding to one of two points central or anterior in the ACL's tibial attachment, led to length change during flexion of the knee [15]. Furthermore, Haberli et al., more recently, reported that in augmented ACL suture repair dispersion of tunnel positions of only a few millimetres around their associated isometric points could already lead to an increase of 4.0-20.9 mm of anterior tibial translation across the arc of flexion of the knee [11]. The extent of dispersion of the actual femoral and tibial tunnel positions - even when targeting for their associated isometric point - in the present study implies that isometric positioning of the augmentation braid is not reliable in augmented ACL suture repair. This leads to slackening/tightening of the augmentation braid across the arc of flexion of the knee, which leaves the suture-repaired ACL either unprotected or stretched; not only after static augmentation, but possibly also after dynamic augmentation, which can only compensate for 8 mm of length change [11].

This implication was further illustrated in recent biomechanical studies of ACL repair in human cadaveric knees where, in contrast with a dynamic augmentation technique, increased anterior tibial translation after cyclic loading of the knee was reported in ACL suture repair with a static augmentation technique [8, 9]. This suggests that in these biomechanical studies, tunnel placement was anisometric (but within the compensatory limits of the dynamic augmentation device), leading to elongation of the static augmented ACL [8, 9]; the results of the present study support this.

Locating the isometric femoral and tibial points of the ACL macroscopically during arthroscopy is known to be difficult [23, 24], and the insertion pattern of the femoral and tibial ACL attachments are variable [25]. This could be compensated by the fact that the intended

isometric points are positioned at the borders of the tibial and femoral ACL attachments (the anterior border of the ACL's tibial attachment and the proximal part of the femoral attachment along Blumensaat's line, as described by Friederich et al. (Figure 1)). With the native ruptured ACL in situ, these positions would be more readily visible than an isometric point combination within the ACL's tibial and femoral attachments [14-16].

In this study, the largest deviations from the desired isometric points were the relatively posterior positions of some tibial tunnels. This might have been a systematic error, caused by the surgeon's habit of placing the tunnel more centrally in the ACL's tibial attachment in ACL reconstruction. The tibial position has less effect on isometry than does the femoral, but it does have some effect [26]. Sidles et al. found that an anterior tibial position was paired with a relatively posterior femoral isometric position, while a more central tibial tunnel corresponded to a position close to the end of Blumensaat's line, as in the present study [27]. A more-posterior tibial augmentation braid position will be at less risk of impingement when the knee is extended, although less well oriented to resist tibial anterior translation [28, 29]. Several studies have found that high-low positions on the femur were less important for isometry than the shallow-deep position, so the offset drill guide used in the present experiment would not have led to large length changes with knee flexion [16, 26, 29]. The most important factor for isometry is the deep-shallow position of the femoral tunnel, and a number of studies have found the isometric point to be at the proximal edge of the ACL attachment, at the posterior end of Blumensaat's line, as used in the present study [16, 29-31]. Use of an image intensifier during tunnel placement might improve tunnel position and decrease anisometry. Furthermore, a dynamic augmentation device could neutralize some length change (up to eight mm) across the arc of flexion of an anisometrically positioned small diameter augmentation braid, and resulting cyclic loading and elongation of the sutured ACL [11].

Whether the remaining anterior tibial translation after static augmented ACL suture repair in biomechanical studies has clinical consequences remains a question unanswered [11, 32-34]. Static augmentation in ACL suture repair has been investigated in several in-vivo animal model studies and a beneficial effect on the structural properties of the suture repaired ACL was reported [35-37]. However, in contrast to dynamic augmented ACL suture repair, anterior tibial translation was not restored to normal values nor was anterior tibial translation reduced further compared to non-augmented ACL suture repair only [12, 35, 37].

Mackay et al. described their static augmented ACL suture repair technique as a check-rein, only shielding the suture repaired ACL when it is stretched beyond its physiological range, implying that there would be no need for isometric tunnel placement for the augmentation braid [32]. In line with several other clinical studies reporting on outcome after ACL suture repair with static augmentation, Mackay et al. reported good subjective results one and two year(s) postoperatively, although there was no mention of results of physical examination, and therefore of the presence of residual anterior tibial translation[32, 34, 38, 39]. Two clinical studies evaluating static augmented ACL suture repair that did measure instrumented side-to-side difference in the Lachman test reported no difference compared to ACL reconstruction, but only in small sample sizes[40, 41]. Furthermore one of these studies reported a significantly higher failure rate compared to ACL reconstruction[40]. More clinical studies are needed to investigate if residual anterior tibial translation occurs after static augmented ACL suture repair and what the implication would be.

Limitations

This study has limitations that have to be addressed. First, the measurements in the present study were performed on digital photographs and not on radiographs as is common in the literature. The findings in the present study for the relative position of the tibial isometric point in antero-posterior and medio-lateral direction on the digital photograph of the tibial plateau -which correspond with the anterior border of the tibial ACL attachment and the centre of the tibial ACL AM attachment respectively- are on par with the corresponding landmarks found in the literature using the same measurement techniques on radiographs [17, 21, 42]. This seems to validate the method used in the present study, translating the measurement of the anteroposterior size of the tibial plateau from the sagittal to the axial plane, and projecting it on a digital photograph of the specimens' tibial plateau rather than on a (sagittal or axial) X-ray.

Second, the grid method described by Bernard et al. was used to investigate the relationship between the actual femoral tunnel and the intended femoral isometric point positions [20]. Although this grid method was previously used to describe various known landmarks of the femoral ACL attachment, no reference with this grid-method for the position of the intended femoral isometric point that was used in the present study existed. However, with good to excellent ICC's this reference point was established in the present study with high reproducibility.

Third, one surgeon has performed the surgery only, which means all data provide information about the skills for tunnel placement of that surgeon. Data for tunnel positions from more than one surgeon would allow to better estimate the impact on tunnel dispersion

in augmented ACL suture repair. Nevertheless, an experienced ACL surgeon performed the surgery, and, with the ruptured ends of the ACL in situ in-vivo, ACL suture repair performed by less experienced surgeons is hypothesized to increase the dispersion of tunnel positions. This extended dispersion would further endorse the conclusion of the current study.
Fourth, although in ACL reconstruction wide variation in tunnel position is known, it has not been studied before in the context of ACL repair [23, 24]. In ACL suture repair, with the ruptured end of the ACL in situ and smaller tunnel size, this could have a negative effect on tunnel placement and anisomety of the augmentation braid when compared to ACL reconstruction.
Fifth, perioperative circumstances during cadaveric studies do not represent in-vivo circumstances. However, in suture repair of the acutely ruptured ACL in-vivo, a hemarthrosis is present impeding visibility to a further extent and the ruptured ends of the ACL are not as clean-cut and close to the femoral attachment as in the present study, therefore probably making tunnel positioning more difficult than in a cadaveric study. This might influence in-vivo results in a negative manner compared to this study.

The clinical relevance of this study is that the extent of dispersion of the position of both the femoral and tibial tunnels away from their intended isometric positions may cause cyclic length changes with knee motion. An ACL suture repair with static braid augmentation will thus be vulnerable to cyclic stretching-out. Consequently, in an era where (static) augmented ACL suture repair is increasingly being performed, the difficulty of obtaining an isometric tunnel combination for the small diameter augmentation braid may influence the clinician's choice between non-, static or dynamic augmented ACL suture repair techniques.

CONCLUSION

This cadaveric study found that in augmented ACL suture repair, with the ruptured ACL in situ, there was dispersion of the positions of the actual small diameter femoral and tibial augmentation braid's tunnels away from their desired isometric points.

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CHAPTER 5

Standard MRI may not predict specific acute ACL rupture characteristics

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ABSTRACT

Background: There has been renewed interest in the concept of anterior cruciate ligament (ACL) suture repair (ACLSR). Morphologic characteristics of the ruptured ACL remnant play a role in deciding whether a patient is eligible for ACLSR. However, no classification of these characteristics of ACL rupture on magnetic resonance imaging (MRI) scans has yet been compared to intraoperative findings in the context of ACLSR.

Purpose: To investigate the value of using preoperative MRI to predict specific characteristics of acute complete ACL rupture.

Study Design: Cohort study (diagnostic); Level of evidence, 2.

Methods: A total of 25 patients were included. Two radiologists classified ACL rupture location and pattern on a preoperative 1.5-T MRI scans with standard sequence; the results were compared with the corresponding findings at arthroscopy conducted by a single surgeon. The agreement between the MRI and surgical findings was calculated using Cohen κ values. Furthermore, the reliability coefficients of the MRI classifications within and between radiologists were calculated.

Results: The agreement between MRI classification and arthroscopic findings for ACL rupture location was slight (Cohen κ, 0.016 [radiologist 1] and 0.087 [radiologist 2]), and for ACL rupture pattern, this was poor to slight (Cohen κ, <0 and 0.074). The intraobserver reliability of MRI classification for ACL rupture location was moderate for radiologist 1 and slight for radiologist 2 (Cohen κ, 0.526 and 0.06, respectively), and for ACL rupture pattern, this was slight for radiologist 1 and 2 (Cohen κ, 0.051 and 0.093, respectively). The interobserver reliability of MRI classification for ACL rupture location and ACL rupture pattern was slight between radiologists (Cohen κ, 0.172 and 0.040, respectively).

Conclusion: In the current study, we found poor to slight agreement between MRI classification and arthroscopic findings of specific ACL rupture characteristics. In addition, the intra- and interobserver reliability for MRI classification of the ACL rupture characteristics was slight to moderate.

Clinical relevance: The results show that 1.5 Tesla MRI with standard scan sequence does not seem to be a feasible diagnostic tool to predict specific characteristics of ACL rupture found at time of surgery, and therefore patients who might be eligible for ACLSR.

INTRODUCTION

There has been renewed interest in the concept of anterior cruciate ligament (ACL) suture repair (ACLSR) rather than ACL reconstruction (ACLR) using a tendon graft. Several promising short-term results for modern augmented and nonaugmented arthroscopic ACLSR techniques have been published [10]. Although an ideal surgical technique and insight in ideal ACL rupture characteristics aimed at optimizing the outcomes have not yet been established, the ACL rupture location, the ACL rupture pattern, and disruption of the synovial sheath have been reported to influence the outcomes of ACLSR [2, 6, 10, 13, 21, 29]. It has been shown that when these morphologic characteristics are assessed at the time of surgery, a substantial number of ruptured ACLs are deemed unrepairable, and instead these patients undergo ACLR [30]. However, the timing at which ACLSR and ACLR are performed is different. Typically, dynamic augmented ACLSR is performed within three weeks after injury, whereas ACLR can be performed at a later time, after the criteria for recovery of knee function have been met [8, 10, 15-17, 35].

Preoperative assessment of these characteristics of ACL rupture using magnetic resonance imaging (MRI) may be useful in the decision making regarding ACLSR for complete ACL rupture. In general, the value of using MRI to diagnose partial or complete ACL tears as well as to locate a partial ACL tear in the anteromedial or posterolateral bundle has been established, and MRI findings have been compared with those at the time of surgery [5, 23]. However, there is paucity in literature comparing pre-operative MRI findings to surgical findings regarding specific characteristics of complete ACL rupture that are relevant to ACLSR (ie, ACL rupture location, ACL rupture pattern, and disruption of the synovial sheath) [18, 31].

In a 2019 randomized controlled trail (RCT), Hoogeslag et al.[9] reported no inferiority for dynamic augmented ACLSR as compared with ACLR in terms of subjective patient-reported outcomes. In all patients, characteristics of acute complete ACL rupture were classified at the time of surgery [8, 9]. However, these were not yet compared with the characteristics of ACL rupture on the corresponding preoperative MRI scans. Therefore, the purpose of this study was to investigate the value of using preoperative MRI to predict morphologic characteristics of acute complete ACL rupture in patients who participated in the RCT. Our hypotheses were that (1) MRI would be accurate for classifying specific characteristics of ACL rupture as compared with findings at time of surgery and (2) classification of

specific characteristics of ACL rupture on MRI scans would be reliable within and between radiologists.

MATERIALS AND METHODS

Patients

This cohort study compared characteristics of ACL rupture classified at the time of surgery with those classified on preoperative MRI scans. Patients were selected from the 2019 RCT of Hoogeslag et al.[9] In the RCT, during the study period of January 2015 to March 2016, a total of 48 patients with acute complete ACL rupture were randomized to undergo either dynamic augmented ACLSR within 3 weeks after injury (*n* = 24) or ACLR after meeting criteria for recovery of knee function (*n* = 24) [9, 16, 17]. In addition, 3 patients underwent dynamic augmented ACLSR before the RCT to reduce the learning curve effect of the surgical technique during the study. See Hoogeslag et al.[9] for the RCT procedures and outcomes.

All 27 patients who underwent ACLSR had surgery within 3 weeks after injury, with a median of 14 days (interquartile range [IQR], 12-17). In contrast, all 24 patients that underwent ACLR were operated >3 weeks after injury, with a median of 47 days (IQR, 42-71). Given that morphologic changes of ruptured ACL remnants are known to occur as soon as 3 weeks after injury and this could interfere with the comparability of MRI findings versus those at the time of surgery, only patients who underwent ACLSR (n=27) were included in the present study [4, 9]. Patients included in the RCT who underwent MRI of the injured knee elsewhere were excluded from the present study.

ACL rupture classification at the time of surgery

All surgical procedures started with standard arthroscopy of the knee, with joint lavage for hemarthrosis. Afterward, ACL rupture characteristics were classified by location (proximal, middle, or distal third), pattern (not lacerated or lacerated into 2 parts or > 2 parts), and the integrity of the synovial sheath (completely, ≥50%, or <50% intact), as described by Henle et al. (Fig. 1) [8].

The described characteristics of ACL rupture were assessed by visual inspection, probing of the ligament remnants, and tensioning of the ligament remnants using a grasper. One surgeon (RAGH) with considerable experience in ACL surgery performed all the surgical procedures and ACL rupture classifications, and the findings were documented in an

operative report form. The surgeon was not blinded to the preoperative MRI scans during the surgical procedure. However, classification of specific characteristics of ACL rupture on MRI scans was performed at a later time, in the context of the present study; as such, this did not influence classification at the time of surgery.

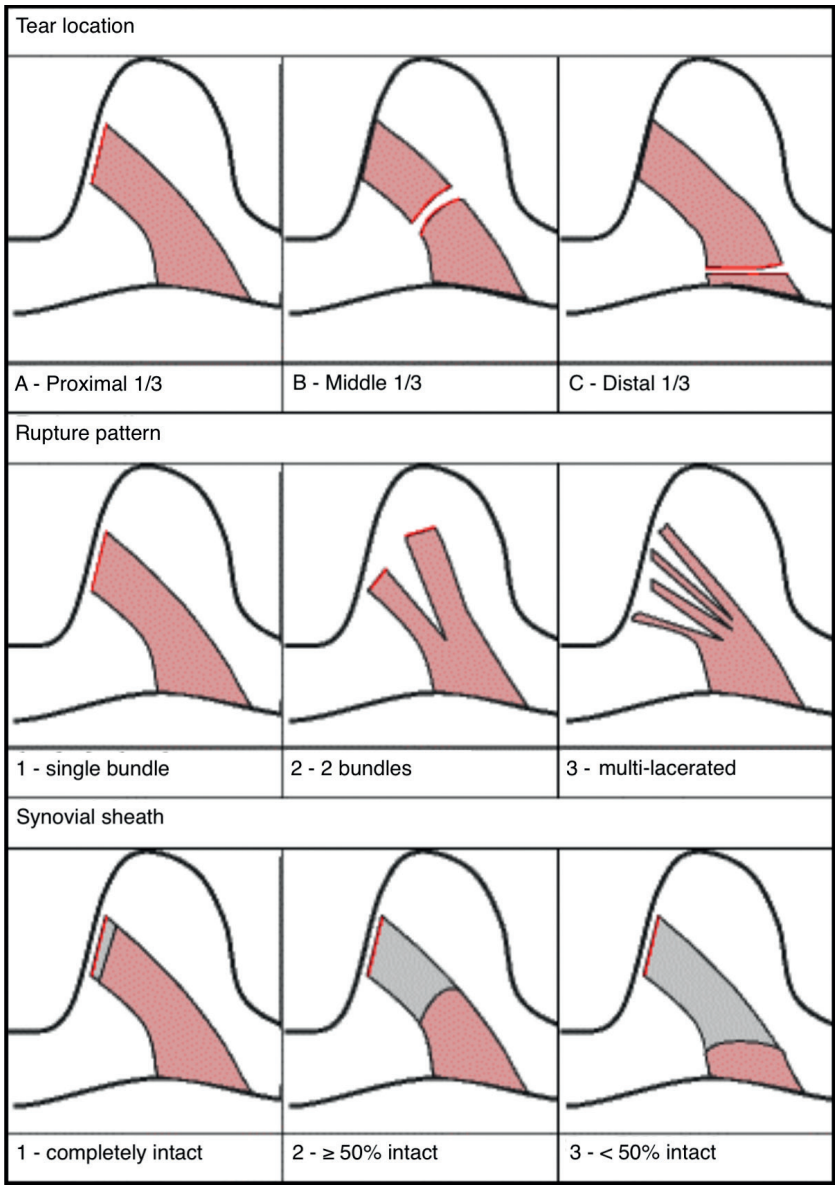

Figure 1. Classification of complete anterior cruciate ligament rupture characteristics at time of surgery based on the rupture location, the rupture pattern, and integrity of the synovial sheath [8]. Image from Henle et al[8]. Reproduced with permission from BMC/Springer Nature.

MRI scan and ACL rupture classification

All MRI of the included patients was performed using a 1.5-T MRI scanner (MAGNETOM Avanto fit; Siemens) according to a standardized scan protocol for the knee (Table 1). All examinations were performed with the patients in the supine position and their knees in extension and without sedation or anesthesia. The knee was supported by a pillow and secured by an extremity coil (Tx/Rx 15-Channel Knee Coil; Siemens).

All MRI scans were assessed using JiveX DICOM Viewer software (Visus Technology). The same classification system that was used during assessment at the time of surgery was used for MRI assessment of the ACL rupture characteristics (Fig. 2) [8]. To determine the ACL rupture location on the MRI scan, first the central point of the femoral ACL attachment was determined in the transverse plane, which was then correlated to the sagittal and coronal planes using a localizer. The same procedure was followed to determine the center of the ACL attachment on the tibia. Finally, the distance between these points was measured and divided into three equal parts, representing the proximal, middle, and distal thirds of the native ACL, and the assessed ACL rupture location was accordingly classified. The ACL rupture pattern was classified on the basis of the severity of laceration seen, using all scan directions. The integrity of the synovial sheath was not radiologically classified, as this is only assessable via MRI using specific sequences and/or contrast and these data were not available [11]. The radiologists were blinded for the surgical findings.

Table 1. Sequences of the standard magnetic resonance imaging (MRI) scan protocol for the knee.

Settings	Turbo Spin Echo Sagittal Oblique Scan		Turbo Spin Echo Fat Suppressed	
	T1-Weighted	Proton Density Fat Supressed	T2-Weighted Coronal Scan	Proton Density Transversal Scan
Repetition time, ms	520.0	3,950.0	3,010.0	2,880.0
Echo time, ms	13.0	37.0	42.0	39.0
Flip angle, deg	180	150	150	150
Echo trains per slice	99	27	13	12
Echo spacing, ms	12.8	9.34	8.46	9.68
Bandwidth, Hz/Px	130	171	191	193
Field of view, mm	180	180	165	160
Slice thickness, mm	3.0	3.0	3.0	3.0
Spacing between slices, mm	0.3	0.3	0.3	0.3
Echo train length	3	10	9	10
Acquisition matrix	480, 0, 0, 358	384, 0, 0, 307	0, 320, 334, 0	0, 320, 240, 0

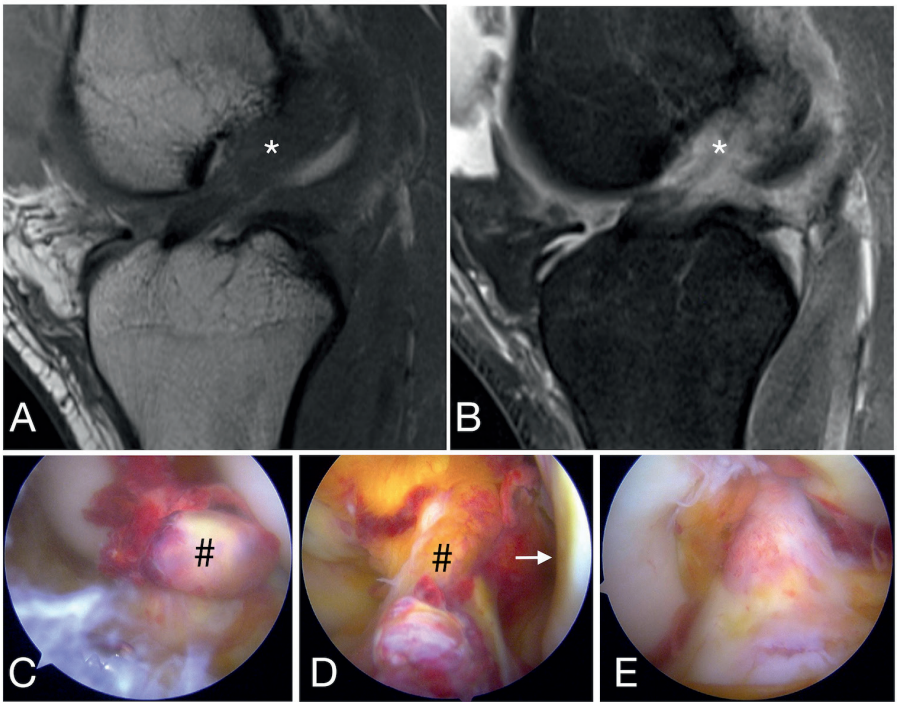

Figure 2. Preoperative magnetic resonance imaging scans and arthroscopic images at the time of surgery of the same knee. Sagittal (A) T1 and (B) T2 views of the knee show the region of the anterior cruciate ligament (ACL) rupture (*). Arthroscopic views of the same knee: (C) ACL rupture (#), (D) "empty wall sign" (arrow), and (E) after dynamic augmented ACL suture repair.

Data collection

Baseline characteristics of the included patients including sex, side of injury, body mass index, age at the time of knee injury, time from injury to surgery, time from injury to the MRI scan, and time from the MRI scan to surgery were recorded. Two experienced musculoskeletal radiologists (SMR and SPHD) separately performed the described MRI classification on 2 occasions 12 weeks apart, and their findings were documented and tabulated. The documented classifications of the ACL rupture characteristics at the time of surgery of the included patients were retrieved from the operative report form and tabulated.

Statistical analyses

For classification of ACL rupture location pattern, the agreement between MRI scans and surgery was calculated using the single-measure 2-way absolute agreement intraclass correlation coefficient (Fig. 3) [14]. Furthermore, to calculate the intra- and interobserver reliability of MRI findings within and between radiologists, the same procedure was followed.

The resulting Cohen κ values were interpreted as poor (<0.00), slight (0.00–0.20), fair (0.21–0.40), moderate (0.41–0.60), substantial (0.61–0.80), or almost perfect (0.81–1.00), according to the guidelines outlined by Landis and Koch [14]. All statistical analyses were performed using SPSS Statistics 24 (IBM Corp).

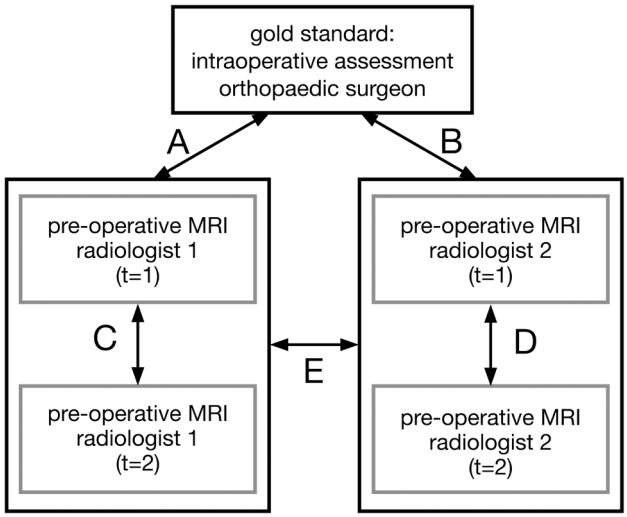

Figure 3. Overview of the collected data and statistical analysis. (A, B) Accuracy of the MRI findings compared to the finding at the time of surgery for ACL rupture location and ACL rupture pattern. (C, D) Intraobserver reliability within and (E) interobserver reliability between (E) the radiologists' MRI findings for ACL rupture location pattern. The time between the initial (t = 1) and the second (t = 2) MRI assessments was 12 weeks. ACL, anterior cruciate ligament; MRI, magnetic resonance imaging.

RESULTS

Of the 27 patients who underwent ACLSR, 2 had undergone preoperative MRI elsewhere before referral to our clinic and were excluded. The remaining 25 patients underwent preoperative MRI of the knee at our clinic and were included in the study. Table 2 shows the baseline characteristics of the included patients. The median time between injury and surgery -and therefore between injury and the classification of ACL rupture characteristics- was 14 days (IQR, 12–16.5; range, 9–20), and the median time between MRI and surgery was eight days (IQR, 5–10; range, 1–15). At the time of surgery, the ACL rupture location was classified as proximal third in 84% of the cases (n = 21), middle third in 12% (n = 3), and distal third in 4% (n = 1), whereas the ACL rupture pattern was classified as not lacerated in 8% (n = 2), lacerated into 2 parts in 40% (n = 10), and multilacerated into > 2 parts in 52% (n = 13).

Table 2. Baseline Characteristics [a]

Characteristics	Patients (*N*=25)
Sex	
Male	21 (84)
Female	4 (16
Age, y	21 (17-31)
Side of injury	
Left	10 (40)
Right	15 (60)
Body mass index	23.1 (21.4-24.5)
Time from, d	
Injury to repair	14 (12-16,5)
Injury to MRI	5 (1-14)
MRI scan to repair	8 (5-10)

[a] As the data were not normally distributed, they are expressed as a median (interquartile range) or frequency (percentage). MRI, magnetic resonance imaging.

Agreement between MRI and surgical findings

Table 3 presents the agreement between MRI classification and the arthroscopic findings for ACL rupture location and ACL rupture pattern. The agreement for the ACL rupture location was slight (Cohen κ, 0.016 [radiologist 1] and 0.087 [radiologist 2]), and the agreement for the ACL rupture pattern was poor to slight (Cohen κ, <0 and 0.074, respectively).

Table 3. Agreement between MRI classification (Radiologist 1 and 2) and surgical findings of ACL rupture location pattern [a]

	Cohen κ	
	Rupture location	Rupture pattern
Surgeon vs radiologist 1 (*N* = 50)	0.016	–0.012
Surgeon vs radiologist 2 (*N* = 50)	0.087	0.074

[a] ACL, anterior cruciate ligament; MRI, magnetic resonance imaging.

Intra- and interobserver reliability for MRI classification of ACL rupture characteristics

Table 4 presents the intra- and interobserver reliability for MRI classification of ACL rupture location and pattern by 2 radiologists. The intraobserver reliability for the ACL rupture

location was moderate for radiologist 1 and slight for radiologist 2 (Cohen κ, 0.526 and 0.061, respectively). The intraobserver reliability for the ACL rupture pattern was slight for radiologists 1 and 2 (Cohen κ, 0.051 and 0.093, respectively). Furthermore, the interobserver reliability for the ACL rupture location and pattern was slight between the radiologists (Cohen κ, 0.172 and 0.040, respectively).

Table 4. Intra- and inter-observer reliability (Cohen's kappa) for MRI classification of ACL rupture characteristics by the radiologists [a]

	Cohen κ	
	Rupture Location	Rupture Pattern
Intraobserver reliability, measurement 1 vs 2		
Radiologist 1 (*N* = 25_)	0.526	0.051
Radiologist 2 (*N* = 25_)	0.061	0.093
Interobserver reliability		
Radiologist 1 vs radiologist 2 (*N* = 50)	0.172	0.040

[a] ACL, anterior cruciate ligament; MRI, magnetic resonance imaging.

DISCUSSION

The most important finding of the present study is that the agreement was poor to slight between the MRI classification of ACL rupture characteristics and the findings at the time of surgery. In addition, intra- and interobserver reliability was slight to moderate for MRI classification of ACL rupture characteristics by the radiologists.

In general, MRI has been established as a valuable diagnostic tool for the evaluation of ACL injuries [23]. However, studies investigating this have focused on the presence of a complete or partial ACL rupture and not on the presence of the characteristics of acute complete ACL rupture that were investigated in the present study [23]. Additionally, although MRI findings to diagnose ACL rupture and to differentiate between the anteromedial or posterolateral bundle in a partial ACL tear have been compared to those at surgery, no MRI findings on characteristics of complete ACL rupture relevant to ACLSR have been compared with those at surgery [5, 18, 31]. Van der List and DiFelice retrospectively classified the characteristics of acute ACL rupture using preoperative MRI and analyzed the frequency with which either ACLSR or ACLR were performed [30]. They reported that assessing the ACL rupture location and the quality of tissue on preoperative MRI scans can predict whether a patient is eligible for ACLSR. Interestingly, while patients were reported to undergo ACLSR only when the

length and tissue quality of the tibial ACL remnant was sufficient, some were retrospectively classified as having an ACL rupture location in the middle 25–75% on the preoperative MRI scan [30]. Although no direct comparison of MRI and surgical findings was performed, this implies that (at least) in these patients, the classification at the time of surgery was not correlated with the retrospective MRI classification of the ACL rupture location. In contrast, in the present study, preoperative MRI findings were compared to their corresponding surgical ones, and the results showed that the ability of the MRI findings to predict specific ACL rupture characteristics was poor to slight. This suggests that 1.5-T MRI with a standard clinical MRI sequence is currently not a feasible diagnostic tool to accurately classify ACL rupture characteristics relevant to ACLSR.

The limited reliability coefficients within and between the radiologists for MRI assessment of ACL rupture characteristics in the present study could be explained by the following: first, as a primary sign of ACL rupture, clear gap formation is not always present on MRI scans; second, precisely locating and grading acute ACL injuries can be obscured by injury-inflicted hemorrhage and edema, which are present in the majority of cases [32-34, 36]. Present primary signs of ACL rupture will not always be well defined and therefore might sometimes overlap with the defined ACL rupture location zones. In contrast, Van der List et al. reported higher reliability coefficients for the classification of the ACL rupture location in a sample comparable to that of the present study (30 patients) with acute ACL rupture; the reliability coefficient for classification of the ACL rupture pattern, which was only slight in the present study, was not analyzed [31]. This difference in the findings could be attributed to several reasons. First, 2 out of 3 observers were already familiar with the radiologic classification system. The third observer was a radiologist who was new to the classification system, like the observers in the present study, and had a lower intraobserver reliability score than did the other 2 observers. This implies that familiarity with the classification system might improve the results.

Second, a different classification system was applied (modified Sherman), which provides more differentiation of the ACL rupture location in the proximal half as compared with the classification system applied in the present study [27, 31]. As the majority of the ACL ruptures are located in the proximal half of the ACL, this might have favored the results of Van der List et al. [8, 31].

Third, despite being sufficient in both studies, the time between the first and second MRI assessment was 3 weeks, as opposed to 12 weeks in the present study, thereby reducing the risk of recall bias among the radiologists.

Fourth, reliability coefficients were calculated for 30 patients randomly selected from a larger group of 353 patients, who were scanned with a either a 1.5- or 3.0-T MRI (not specified for this subgroup), as compared with 1.5-T in the present study [31]. However, field strength alone does not necessarily result in a better resolution of the MRI scan. Having a smaller slice thickness (3.0 vs 3.5 mm) which increases signal-to-noise ratio, having a small gap (0.3 mm vs no gap) which decreases interference between adjacent slices, and using a dedicated knee coil with a larger number of receiver-channels (15-channels versus 8-channels) would have resulted in a better spatial resolution in the present study [24, 28]. Nevertheless, Van der List et al. reported reliability coefficients for MRI assessment of ACL rupture location that were substantially higher than the values in the present study.

There have been some reports of excellent outcomes with augmented ACLSR for midsubstance ACL rupture with the addition of a bridging collagen scaffold, which might, at least in part, eliminate the decision making between ACLSR and ACLR on the basis of specific ACL rupture characteristic in the future [3, 6, 7, 10, 19]. However, it seems that for now the final assessment of a patient's eligibility for ACLSR should be made at the time of surgery. Nevertheless, the value of using MRI in the classification of specific characteristics of acute complete ACL rupture might be improved in several ways compared to the 1.5-T MRI with a standard sequence that was used in the present study. Although the capabilities of 1.5-T and 3.0-T MRI scanners are not significantly different in the diagnosis of ACL rupture in general, higher field strength improves the signal-to-noise and contrast-to-noise ratios [28]. Higher field strength together with a small field of view and a dedicated knee coil with a larger number of receiver-channels can optimize the spatial resolution, which may allow better visibility of the specific ACL rupture characteristics [24]. Additional oblique scans in the coronal and axial planes improve visualization of the ACL, and a 3-dimensional MRI sequence might provide more information on the ACL rupture characteristics [1, 12, 20, 22, 25, 26]. Furthermore, it has been reported that MRI with the knee in flexion instead of extension improves accuracy in the diagnosis of partial and complete ACL ruptures in general. Although not investigated, this might also improve accuracy of MRI for classifying the characteristics of complete ACL rupture that were investigated in the present study [18].

Limitations

This study has some specific limitations that need to be addressed. First, only 1 observer assessed the classification of the ACL rupture characteristics at the time of surgery. However, in ACLR procedures, it is common practice that decisions at the time of surgery are made by just 1 orthopedic surgeon. In addition, assessments are based not only on

the arthroscopic image but also on probing of the ruptured ACL remnants at the time of surgery. Although arthroscopic images were available for all the included patients, probing could not be replicated by assessing only arthroscopic images. As such, the single-surgeon classification of ACL rupture characteristics at the time of surgery can be considered the current gold standard.

Second, although this study included a relatively small sample size, it was large enough to reject the null hypothesis. Additionallly, while important for decision making in surgical timing and technique, there is paucity in studies concerning the investigated topic. This study is the first to validate specific rupture characteristics of acute complete ACL rupture on preoperative MRI scans against findings at the time of surgery in the context of ACLSR.

Third, the distribution of the ACL rupture characteristics in the present study differed from that reported by Henle et al., who had a much larger sample size (278 patients), and might not represent the normal distribution of the ACL rupture characteristics in the general population [8]. In the present study, the reported frequency of a multilacerated ACL rupture pattern was higher compared to that reported by Henle et al. This further obscures the assessment of the ACL rupture characteristics and might have negatively affected the current results.

Fourth, the morphology of ruptured ACL remnants is known to change over time. Although MRI and surgery were not performed on the same day, the median time between MRI and surgery was 8 days (IQR, 5–10, range, 1–15). Thus, no relevant morphologic changes were expected between the time of MRI and surgery. Furthermore, as the median time between injury and surgery was 14 days (IQR, 12–16.5, range, 9–20) and morphologic changes were reported to occur from 3 weeks on after injury, no major morphologic changes in the ACL remnants between MRI and surgery were expected from this perspective.

CONCLUSION

In the current study, we found poor to slight agreement between MRI classification and arthroscopic findings of specific ACL rupture characteristics. In addition, the intra- and interobserver reliability for MRI classification of the ACL rupture characteristics was slight to moderate.

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CHAPTER 6

Acute Anterior Cruciate Ligament Rupture: Repair or Reconstruction? Two-Year Results of a Randomized Controlled Clinical Trial

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ABSTRACT

Background: Contemporary ACL suture repair techniques have been subject to regained interest in recent years. Although several clinical studies have yielded good short-term results, high-quality evidence is lacking in regard to the effectiveness of this treatment compared to ACL reconstruction.

Hypothesis: Dynamic augmented ACL suture repair is at least as effective as anatomic single-bundle ACL reconstruction for the treatment of acute ACL rupture in terms of patient self-reported outcome at 2 years postoperatively.

Study Design: Randomized Controlled Clinical Trial; Level of evidence, 1.

Methods: After stratification and randomization, 48 patients underwent either dynamic augmented ACL suture repair or ACL reconstruction with a single-bundle, all-inside, semitendinosis technique. The International Knee Documentation Committee (IKDC) subjective score at 2 years postoperatively was the primary outcome measure. Patient-reported outcome (IKDC subjective score, Knee injury and Osteoarthritis Outcome Score, Tegner score, visual analog scale for satisfaction), clinical outcomes (IKDC physical examination, leg symmetry index for the quadriceps, hamstrings strength and jump test battery), and radiological outcomes as well as adverse events including re-ruptures were recorded. Analyses were based on an intention-to-treat principle.

Results: The lower limit for the median IKDC subjective score of the repair group (86.2) fell within the prespecified noninferiority margin, confirming noninferiority of dynamic augmented ACL suture repair to ACL reconstruction. No statistical difference was found between groups for median IKDC subjective (repair, 95.4; reconstruction, 94.3). Overall, 2 reruptures (8.7%) occurred in the dynamic ACL suture repair group and 4 reruptures (19.0%) in the ACL reconstruction group; further, 5 repeat surgeries -other than for revision ACL surgery- took place in 4 patients from the dynamic ACL suture repair group (20.8%) and 3 in 3 patients from the ACL reconstruction group (14.3%).

Conclusion: Dynamic augmented ACL suture repair is not inferior to ACL reconstruction in terms of subjective patient-reported outcomes as measured with the IKDC subjective, 2 years postoperatively. However, for reasons other than revision ACL surgery due to rerupture, a higher number of related adverse events leading to repeat surgery were seen in the dynamic augmented ACL suture repair group within 2 years postoperatively.

Clinical Relevance: Dynamic augmented ACL suture repair might be considered as a viable treatment option for patients with an acute ACL rupture.

INTRODUCTION

Suture repair of the ruptured anterior cruciate ligament (ACL) has been subject to renewed interest in recent years with the advent of contemporary arthroscopic techniques using static or dynamic or no augmentation.[28, 39, 53, 54] In static augmentation, a tape or braid is fixed to both the tibial and the femoral bones directly, whereas in dynamic augmentation, a braid is fixed to the femoral cortex and to an additional elastic link (spring-in-screw mechanism) on the tibial side.

Although biomechanical studies have shown that only ACL suture repair with dynamic augmentation restored anterior tibial translation (ATT), preclinical porcine and ovine animal studies have shown that both static and dynamic augmented ACL suture repair techniques led to good results.[24, 29, 41, 47, 54, 56] Moreover, promising short-term to midterm results have been reported in retrospective and prospective series using nonaugmented, static augmented, or -mostly- dynamic augmented ACL suture repair techniques.[1, 3, 6, 9, 11, 13, 23, 30, 31, 35, 36, 40, 46, 52] Some authors have even questioned whether these promising clinical results would lead to a paradigm shift in treatment of the acute ruptures of the ACL, away from the current gold standard of autograft ACL reconstruction and back to ACL suture repair.[23, 51, 56]

However, the body of evidence for clinical studies using contemporary ACL suture techniques is rather small, and high-quality evidence is lacking.[54] Therefore, the purpose of this study was to examine patient-reported, clinical, and radiological outcomes of augmented ACL repair compared with ACL reconstruction in patients with an acute rupture of the ACL. The aim was to examine the following null hypotheses: dynamic augmented ACL suture repair is at least as effective as anatomic single-bundle ACL reconstruction in treatment of acute ACL rupture in terms of patient self-reported outcomes 2 years postoperatively.

MATERIALS AND METHODS

A prospective, stratified, block randomized controlled trial (RCT) was conducted at Centre of Orthopaedic Surgery OCON, Hengelo, The Netherlands. The institutional review board approved this study. Patients 18 to 30 years of age visiting the outpatient clinic were screened for eligibility for this study. Eligible patients had a proven primary ACL rupture confirmed by means of history, physical examination, and magnetic resonance imaging; had an indication for ACL reconstruction surgery; could undergo surgery within 21 days after injury; and had a score of 5 to 10 on the Tegner Activity Scale (Tegner).[5, 50] Inclusion was independent of

ACL rupture localization. Exclusion criteria were concomitant ligamentous lesions, meniscal lesions needing surgical repair, and full-thickness cartilage lesions, as these injuries require a change in the postoperative rehabilitation regimen. Further exclusion criteria were a history of knee surgery of the contralateral and/or ipsilateral knee; hypersensitivity to cobalt, chromium or nickel; muscular, neurological or vascular abnormalities; osteoarthritis seen on the weightbearing preoperative radiograph; and tendency to form excessive scar tissue.

Randomization and intervention

After written informed consent was obtained, patient characteristics were recorded and a baseline measurement was performed. Subsequently, patients were stratified using their preinjury Tegner score (moderate, Tegner 5-7; high, Tegner 8-10) to distribute the risk of reinjury based on physical activity level equally between groups, after which patients were randomized by the sports physiotherapist in blocks with varying sizes (sealed envelope, computer generated schedule; n=2 and n=4) to undergo either dynamic augmented ACL suture repair or single-bundle ACL reconstruction with a semitendinosis graft. [5, 50, 57]

Surgical Procedure

Augmented ACL suture repair was performed within 3 weeks after injury. ACL reconstruction was performed within 2 weeks after patients met the preoperative criteria.[55] If these criteria were not met, the patients undergoing an ACL reconstruction underwent preoperative rehabilitation by a sports physiotherapist and were reassessed for presence of preoperative criteria at a later stage. After administration of prophylactic antibiotics and anaesthesia, the surgical procedures started with manual examination and standard arthroscopy with the patient in a supine position, the leg in an electric leg holder and a tourniquet inflated to 300 mm Hg, to assess all compartments for concomitant injury. One surgeon (R.A.G.H.), who has considerable experience in ACL reconstruction surgery, performed all surgical procedures.

Augmented ACL Repair. Augmented ACL suture repair was performed with the dynamic intraligamentary stabilisation technique (Ligamys, Mathys Medical) as described by Eggli et al..[10] Using a suturing forceps, the surgeon tied the tibial stump of the ruptured ACL with 3 or 4 retaining threads (PDS No. 2-0; Ethicon). An aiming device was positioned from the anteromedial aspect of the tibial metaphysis to the center of the tibial ACL attachment, and a 2.4 mm diameter drill tip guide pin was used to create a tibial tunnel of at least 50mm in length. An outside-in tibial socket of 30-mm length and 10-mm diameter was reamed over the tibial guide pin with a cannulated drill, leaving a 20-mm bone bridge between the

top of the tibial socket and the joint line. A Ligamys Monobloc fixation device was screwed inside the tibial tunnel over the guide pin, until it lined up precisely with the tibial cortex. A shuttle thread replaced the tibial guide pin. A femoral tunnel was created with a 2.4-mm diameter drill tip guide pin with eyelet, in the direction of an accessory anteromedial portal, just superior to the tibial plateau and medial meniscus and just anterior to the medial femoral condyle, with the knee in 120 degrees of flexion, to the anteromedial part of the femoral ACL attachment. An incision was made from the skin to the lateral femoral cortex in the trajectory of the guide pin to allow cortical fixation of the button and retaining threads. The shuttle thread in the tibial tunnel and the retaining threads in the ACL stump were led through the femoral tunnel with the femoral drill tip guide pin with eyelet.

The knee was placed in 0 degrees of flexion.[24] After the retaining threads in the ACL stump were tensioned individually and the tibial stump of the ruptured ACL was repositioned to its femoral origin, a Ligamys braid was pulled distally through the femoral and tibial tunnels with the shuttle wire. It was verified that the braid's proximal fixation button abutted the lateral femoral cortex, thereby also fixing the tensioned retaining threads to the femoral cortex. With a tensioning device, the braid was tensioned to maximal manual load and released, after which it was tensioned again to 80 N.[24, 47] A clamping cone was fixed into the Monobloc with a torque screwdriver (Figure 1). The procedure was completed with microfracturing of the notch in and near the femoral attachment. If patients requested removal of the tibial implant, this was performed after 2-year follow-up in order to prevent interference with the primary outcome measure.

ACL Reconstruction. ACL reconstruction was performed with an all-inside technique (Arthrex).[34] The semitendinosus tendon from the ipsilateral leg was harvested with a mini-incision technique at the posterior side of the knee and quadrupled.[44] The remnants of the ruptured ACL were removed, leaving approximately 3 mm of remnant on the tibial and femoral ACL attachment site. Independent tibial and femoral sockets were prepared with a retrograde drill (Flipcutter, Arthrex), with the tibial socket in the center of the tibial ACL attachment and the femoral socket with a bias from the center towards the femoral anteromedial bundle attachment.[34] After advancement and fixation of the graft in the femoral socket, the graft was advanced and fixed in the tibial socket with the knee in 0 degrees of flexion while anterior translation of tibia in relation to femur was reduced manually. Positioning and tension of the graft were verified under arthroscopic view, and the graft tension was adjusted if necessary.

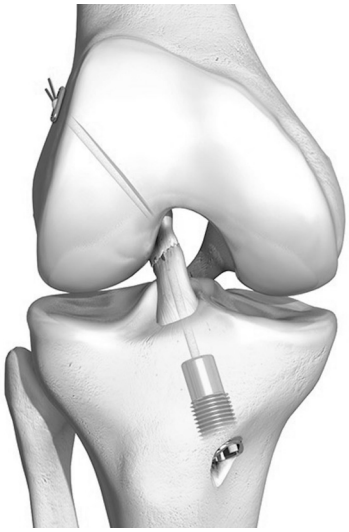

Figure 1. Dynamic augmentation of the ruptured anterior cruciate ligament (ACL). ACL suture repair was augmented with an intraligamentary braid with cortical button fixation on the femoral side and an additional elastic link (a spring-in-screw mechanism) on the tibial side. Reprinted with permission of Hoogeslag et al. [24].

Postoperative Rehabilitation. Both groups received a near-identical, structured, criteria-based rehabilitation protocol and were guided by their own sports physical therapist accordingly.[55] Patients treated with augmented ACL repair received a long-leg splint locked in extension during the first 5 days postoperatively, whereas patients treated with ACL reconstruction were allowed full range of motion as tolerated directly postoperatively.

Baseline characteristics

Patient baseline and peroperative characteristics included in the study were sex, age, injured side, body mass index, smoking status, time from injury to surgery, presence and treatment of concomitant cartilage and meniscal injuries, operating time and ACL rupture classification (location (proximal, midsubstance, or distal tear), type (laceration into one bundle, two bundles, ≥ 3 bundles) and integrity of the synovial sheath (completely intact, ≥50% intact, <50% intact)). [23]

Outcome measures

The primary outcome measure was the International Knee Documentation Committee 2000 (IKDC) subjective score 2 years postoperatively. The IKDC subjective measures symptoms

and functional limitations for a variety of knee disorders, including ligamentous injuries, and is validated in Dutch. [20, 25, 26]

Patients were evaluated at baseline and at 3, 6, 9, 12 and 24 months postoperatively with patient-reported outcome measures (PROMs) and physical examination. The PROMs were IKDC subjective score (range, 0 [worst] to 100 [best]), Knee Injury and Osteoarthritis Outcome Score (KOOS) (range, 0 [worst] to 100 [best]) to assess perceived level of functional recovery; Tegner score (range, 0 [low physical activity) to 10 [high physical activity]) to assess level of physical activity; and a visual analogue scale (VAS) (range, 0 [unsatisfied] to 10 [very satisfied]) to assess level of satisfaction with the outcome of surgery. The physical examination entailed IKDC physical examination score (range, A [best] to D [worst]) and instrumented Lachman testing with a Rolimeter (Aircast).[4, 8, 15, 20, 25, 38, 50]

Leg symmetry index (LSI) for isokinetic quadriceps and hamstrings strength (Isoforce dynamometer, TUR) (peak torque at 60, 180 and 300 deg/s) and for jump tests (single-leg hop and hold, side hop and triple hop for distance) were evaluated at 6, 9, 12 and 24 months postoperatively.[18, 42] LSI for isokinetic quadriceps and hamstrings strength was also evaluated at baseline.[42] Signs of osteoarthritis were scored on the anteroposterior weightbearing and lateral radiographs 1 year and 2 years postoperatively by use of the Kellgren-Lawrence score.[27] Rerupture and repeat surgery, as well as other complications or adverse events, were recorded and extracted from the patients' records. The clinimetric assessments were performed by 2 independent, experienced sports physical therapists in the orthopaedic department's outpatient clinic; for practical reasons, assessors were not blinded for the patients' treatment allocation.

Statistical Analysis

Sample size was calculated based on 1-sided noninferiority of ACL suture repair compared to ACL reconstruction in terms of patient-reported functional outcome measured by the IKDC subjective score. SD was set at 9, and with a reported minimal clinically relevant difference of 8.8 to 15.6 points of the IKDC subjective score this was set at 10.[7, 26, 33] To achieve a statistical power of 90% and an alpha of 5%, a sample size of 20 patients in each study group was required. To allow for a 20% rate of lost to follow-up, 24 patients per group were included, 48 patients in total.

Descriptive results are presented as frequency, percentage or median (interquartile range). Since data were not normally distributed (Shapiro-Wilk test), the Mann-Whitney-Wilcoxon

test was used to investigate differences between groups. Chi-square tests were applied for categorical variables.

To assess whether dynamic augmented ACL suture repair was noninferior to ACL reconstruction regarding the IKDC subjective score 2 years postoperatively, an intention to treat (ITT) analysis was performed.[43] The ITT cohort consisted of patients who completed the IKDC subjective questionnaire at 2-year follow-up.

Dynamic augmented ACL suture repair was considered noninferior to ACL reconstruction if the lower boundary of the 2-sided 95% CI of the IKDC subjective score of the ACL suture repair group at 2-year follow-up lay within the noninferiority margin (Δ = -10 points) of the median IKDC subjective score of the ACL reconstruction group at 2-year follow-up. For nonparametric data, 95% CIs for the median IKDC subjective score at 2-year follow-up were calculated per group by means of the Gardner and Altman formula (http://web1.sph.emory.edu/users/cdckms/median-final.htmlhttp://web1.sph.emory.edu/cdckms/median-final.html). The level of significance was set to <.05. Statistical analyses were performed using SPSS 22.0 (SPSS Inc,) and a *P* value of ≤.05 was considered statistically significant. For secondary outcome measures, in case of multiple testing, the Bonferroni-Holm correction was used to adjust the level of significance.

RESULTS

During the study period of January 2015 to March 2016, 323 of the 375 patients who underwent primary ACL reconstruction did not meet the inclusion criteria preoperatively and 3 patients declined to participate. Of the remaining 49 patients, 1 was excluded peroperatively because of the need for a meniscal suture repair, leaving 48 patients who were included for analysis in this study (Figure 2). During the 2-year follow-up, 1 patient in the ACL reconstruction group was lost to follow-up because of pregnancy and 3 patients were lost to follow-up despite multiple attempts to contact them. In the repair group, 1 patient was lost to follow-up.

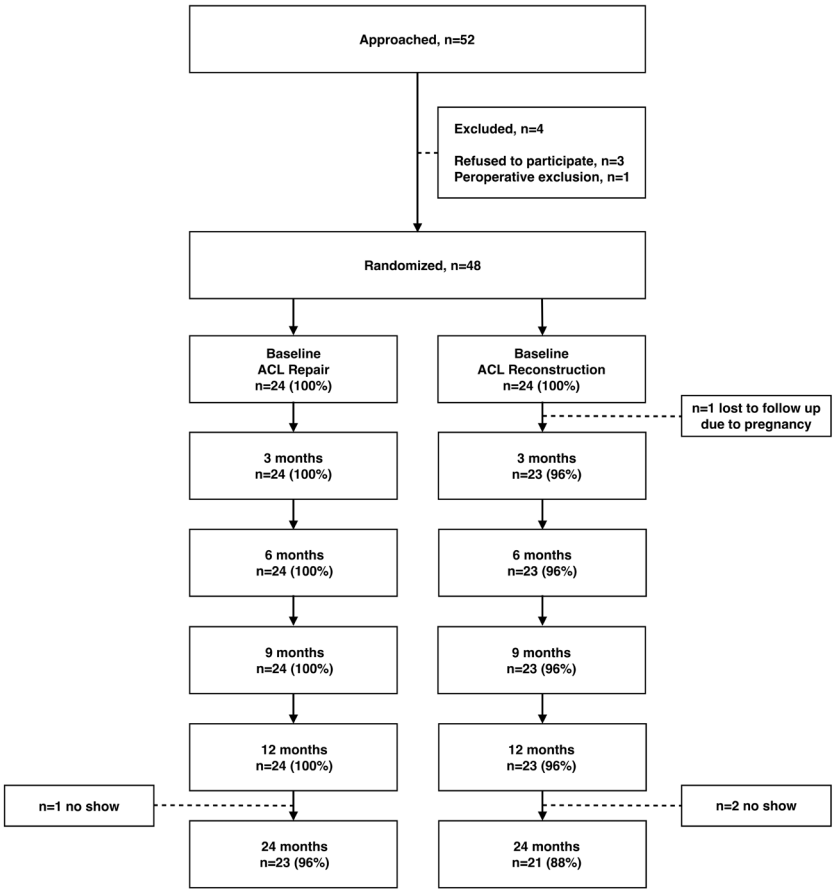

Figure 2. Flowchart inclusion and randomization of subjects. ACL = anterior cruciate ligament.

Baseline and peroperative characteristics

Baseline characteristics are presented in Table 1. No differences were found in baseline characteristics between groups, except for a significant shorter time from injury to surgery (P = .000) and significant longer operating time for dynamic augmented ACL suture repair compared to ACL reconstruction (P <.0001). The variation in KOOS and IKDC subjective scores between patients within both groups was high but not statistically different between groups. In patients requiring partial meniscectomy, no more than 20% of the surface area was resected. For the dynamic augmented ACL suture repair group, rupture in the proximal third (83.3%), with laceration into more than one bundle (87,5%), was most prevalent.

Table 1. Baseline characteristics and peroperative findings.[a]

	Repair (n = 24)	Reconstruction (n = 24)	*P* Value
Sex			.731
Men	19 (79.2)	18 (75)	
Women	5 (20.8)	6 (25)	
Age (years)	21.0 (18.0-27.0)	22.0 (19.3-25.0)	.693
Injured side			.247
Left	9 (37.5)	13 (54.2)	
Right	15 (62.5)	11 (45.8)	
Body mass index	23.0 (21.0-24.5)	23.3 (22.1-24.4)	.445
Smoking			.753
Yes	7 (29.2)	7 (29.2)	
No, never	14 (58.3)	14 (58.3)	
No, quit < 6 mo ago	0 (0.0)	1 (4.2)	
No, quit ≥ 6 mo ago	3 (12.5)	2 (8.3)	
IKDC subjective score	72.4 (49.1-95.2)	59.8 (39.0-100.0)	.438
KOOS			
Other symptoms	96.0 (41.8-100.0)	54.0 (64.0-94.6)	.261
Pain	100 (62.5-100.0)	62.5 (50.8-100.0)	.095
ADL	99.5 (66.8-100.0)	73.5 (57.0-100.0)	.245
Sport & recreation	97.5 (17.5-100.0)	27.5 (6.3-100.0)	.194
Knee-related QoL	97 (44.0-100.0)	53.5 (20.5-100.0)	.208
Tegner	8.0 (7.0-9.0)	8.5 (7.0-9.0)	.893
Tegner stratification			.771
Intermediate	11 (45.8)	10 (41.7)	
High	13 (54.2)	14 (58.3)	
IKDC physical examination score			.671
A	0 (0)	0 (0)	
B	3 (12.5)	4 (16.7)	
C	11 (45.8)	8 (33.3)	
D	10 (41.7)	12 (50.0)	
LSI force ratio i/u	(n = 17)[b]	(n=18)[b]	
Quadriceps 60 deg/s	62.6 (51.9-81.0)	58.1 (40.9-88.1)	.446
Quadriceps 180 deg/s	79.2 (60.3-84.7)	60.9 (47.3-85.5)	.199
Quadriceps 300 deg/s	74.7 (65.0-83.8)	66.7 (58.2-85.2)	.318
Hamstrings 60 deg/s	70.0 (51.7-79.6)	66.9 (30.7-72.3)	.202
Hamstrings 180 deg/s	75.4 (59.1-95.2)	63.7 (27.9-88.6)	.141
Hamstrings 300 deg/s	84.4 (58.5-104.0)	73.7 (48.6-90.1)	.222
Time from injury to surgery, d	13 (12-16)	47 (42-71)	.000
Accompanying injury noted preoperatively			

Table 1. Continued.

	Repair (n = 24)	Reconstruction (n = 24)	*P* Value
Partial medial meniscectomy	3 (12.5)	4 (16.7)	.683
Partial lateral meniscectomy	2 (8.3)	7 (29.2)	.064
Lateral femoral chondral lesion	1 (4.2)	0 (0)	.312
Medial femoral chondral lesion	0 (0)	1 (4.2)	.312
Lateral tibial chondral lesion	0 (0)	1 (4.2)	.312
Medial tibial chondral lesion	0 (0)	0 (0)	
Patellar chondral lesion	0 (0)	1 (4.2)	.312
Operating time, min	61.5 (55.3-68.0)	44.0 (39.0-49.0)	<.0001
ACL rupture location			
Proximal third	20 (83.3)	–	
Central third	3 (12.5)	–	
Distal third	1 (4.2)	–	
ACL rupture bundle			
1 bundle	3 (12.5)	–	
2 bundles	10 (41.7)	–	
≥ 3 bundles	11 (45.8)	–	
ACL rupture sheath			
Completely intact	3 (12.5)	–	
≥50% intact	16 (66.7)	–	
<50% intact	5 20.8)	–	

[a]Since data were not normally distributed, they are expressed as median (interquartile range) or frequencies (percentage). ACL, anterior cruciate ligament; ADL, activities of daily living; IKDC, International Knee Documentation Committee; KOOS, Knee Injury and Osteoarthritis Outcome Score; LSI, leg symmetry index; QoL = quality of life; –, not applicable.

[b]Baseline data LSI were missing because of pain and/or inability to perform LSI tests.

Table 2. Differences between dynamic augmented ACL suture repair and ACL reconstruction over time.[a]

	3 months			6 months			9 months			12 months			24 months		
	Repair	Reconstruction	*P*	Repair	Reconstruction	*P*	Repair	Reconstruction	*P*	Repair	Reconstruction	*P*	Repair	Reconstruction	*P*
IKDC Subjective	69.5	73.6	.406	87.9	86.2	.409	95.4	90.8	.480	95.4	96.6	.663	95.4	94.3	.663
	(62.6-80.2)[b]	(62.1-85.1)[b]		(70.7-93.1)[c]	(79.0-95.1)[c]		(80.5-98.6)[d]	(82.5-97.4)[d]		(87.1-97.7)[c]	(89.9-98.9)[c]		(80.5-100)[e]	(86.5-98.9)[e]	
KOOS															
Other symptoms	71.0	86.0	.011	86.0	89.0	.514	91.0	89.0	.854	93.0	96.0	.653	89.3	92.3	.934
	(64.0-86.0)[b]	(75.0-93.0)[b]		(72.0-96.0)[c]	(82.0-93.0)[c]		(82.0-100.0)[f]	(86.0-96.0)[f]		(79.8-99.0)[c]	(78.5-100.0)[c]		(85.7-96.4)[g]	(78.6-100.0)[g]	
Pain	86.0	92.0	.215	97.0	94.0	.981	97.0	97.0	.657	100.0	100.0	.869	100.0	100.0	.471
	(78.8-92.0)[b]	(81.0-97.0)[b]		(83.0-100.0)[c]	(90.5-100.0)[c]		(88.3-100.0)[f]	(94.0-100.0)[f]		(93.3-100.0)[c]	(95.5-100.0)[c]		(88.9-100.0)[e]	(95.1-100.0)[e]	
ADL	96.0	99.0	.174	100.0	100.0	.796	100.0	100.0	.808	100.0	100.0	.847	100.0	100.0	≥.999
	(87.3-99.0)[b]	(94.0-100.0)[b]		(99.0-100.0)[c]	(97.0-100.0)[c]		(98.5-100.0)[f]	(98.0-100.0)[f]		(100.0-100.0)[c]	(100.0-100.0)[c]		(100.0-100.0)[g]	(99.3-100.0)[g]	
Sport & recreation	62.5	60.0	.966	85.0	85.0	.954	97.5	90.0	.365	100.0	95.0	.668	75.0	75.0	.292
	(40.0-83.4)[b]	(40.0-85.0)[b]		(70.0-95.0)[c]	(70.0-95.0)[c]		(81.3-100.0)[f]	(83.0-100.0)[f]		(86.3-100)[c]	(85.0-100.0)[c]		(68.8-93.8)[g]	(68.8-90.6)[g]	
QoL	63.0	63.0	.331	69.0	75.0	.475	75.0	81.0	.342	78.0	81.0	.705	95.0	100.0	.972
	(50.0-67.5)[b]	(50.0-69.0)[b]		(63.0-81.0)[c]	(69.0-81.0)[c]		(63.0-81.0)[f]	(69.0-94.0)[f]		(63.0-94.0)[c]	(69.0-91.0)[c]		(85.0-100.0)[g]	(90.0-100.0)[g]	
Tegner	4.0	4.0	.903	5.0	5.0	.771	7.0	7.0	.509	7.0	9.0	.682	7.0	7.0	.981
	(3.0-5.0)[b]	(3.0-5.0)[b]		(5.0-6.0)[c]	(4.0-6.0)[c]		(5.0-9.0)[f]	(5.0-9.0)[f]		(6.3-9.0)[c]	(6.5-9.0)[c]		(5.0-9.0)[g]	(5.0-9.0)[g]	
Active at pre-injury Tegner level										14 (58.3)[c]	9 (42.9.)[c]	.172	12 (52.2)[e]	11 (55.0)[e]	.989
VAS satisfaction	8.2	8.5	.594	9.3	8.5	.682	9.1	8.8	.215	9.3	8.9	.814	9.1	9.3	.883
	(6.9-9.5)[b]	(7.5-9.3)[b]		(7.1-9.6)[c]	(7.9-9.9)[c]		(8.3-9.8)[f]	(6.9-9.4)[f]		(8.1-9.8)[g]	(8.4-9.5)[g]		(7.7-10.0)[e]	(7.7-9.8)[e]	
IKDC physical examination			.073			.333			.157			.141			.438
A	5 (20.8)[b]	12 (52.2)[b]		14 (63.6)[f]	16 (76.2)[f]		19 (86.4)[f]	13 (61.9)[f]		19 (82.6)[g]	14 (66.7)[g]		20 (87.0)[h]	14 (77.8)[h]	
B	14 (58.5)[b]	9 (39.1)[b]		6 (27.3)[f]	5 (23.8)[f]		3 (13.6)[f]	7 (33.3)[f]		2 (8.7)[g]	7 (33.3)[g]		3 (13.0)[h]	4 (22.2)[h]	
C	5 (20.8)[b]	2 (8.7)[b]		2 (9.1)[f]	0 (0)[f]		0 (0)[f]	1 (4.8%[f]		1 (4.3)[g]	0 (0)[g]		0 (0)[h]	0 (0)[h]	
D	0 (0)[b]	0 (0)[b]		0 (0)[f]	0 (0)[f]		0 (0)[f]	0 (0)[f]		0 (0)[g]	0 (0)[g]		0 (0)[h]	0 ()[h]	
Lachman delta, mm	2.0	1.0	.149	2.0	1.0	.012	2.0	1.0	.568	1.0	2.0	.098	1.0	1.0	
	(1.0-2.0)[f]	(0.0-2.0)[f]		(2.0-2.0)[e]	(1.0-2.0)[e]		(1.0-2.0)[f]	(1.0-3.0)[f]		(0.0-2.0)[h]	(1.0-2.0)[h]		(0.8-2.0)[h]	0.0-2.0)[h]	.777
LSI force ratio injured/uninjured															
Quadriceps 60 deg/s	–	–	–	77.2	86.0	.209	90.0	99.5	.191	100.0	100.0	.385	93.2	88.2	.854
				(67.0-84.6)[c]	(77.3-97.5)[c]		(81.8-100.3)[i]	(87.3-104.7)[i]		(80.0-106.0)[j]	(92.4-109.0)[j]		(82.4-104.5)[h]	(79.8-116.2)	
Quadriceps 180 deg/s	–	–	–	78.5	92.1	.072	90.5	95.5	.333	92.1	101.5	.222	89.9	92.9	.462
				(66.2-86.2)[c]	(79.8-105.4)[c]		(82.4-97.7)[i]	(84.8-103.3)[i]		(85.4-103.4)[j]	(89.8-107.1)[j]		(84.3-102.5)[h]	(84.3-112.2)[h]	

Table 2. Continued.

	3 months			6 months			9 months			12 months			24 months		
	Repair	Reconstruction	*P*	Repair	Reconstruction	*P*	Repair	Reconstruction	*P*	Repair	Reconstruction	*P*	Repair	Reconstruction	*P*
Quadriceps 300 deg/s	–	–	–	79.5	90.7	.226	93.4	95.6	.433	97.1	97.0	.308	91.0	98.9	.198
				(69.9-91.0)[c]	(81.3-107.7)[c]		(75.9-99.4)[i]	(81.5-105.8)[i]		(81.6-106.1)[j]	(84.4-113.3)[j]		(83.1-100.0)[h]	(84.7-110.0)[h]	
Hamstrings 60 deg/s	–	–	–	96.3	81.5	.724	99.9	82.8	.026[k]	100.3	88.1	.026[k]	99.9	88.7	.080
				(82.5-105.9)[c]	(70.7-92.1)[c]		(87.3-116.6)[i]	(75.6-103.9)		(88.0-116.8)[j]	(78.0-106.7)[j]		(88.1-109.8)[h]	(73.5-98.9)[h]	
Hamstrings 180 deg/s	–	–	–	97.9	89.9	.282	104.2	87.9	.036[k]	107.9	93.8	.054	99.4	86.4	.190
				(85.1-105.9)[c]	(78.2-102.1)[c]		(92.4-114.1)	(75.0-109.0)[i]		(91.0-118.0)	(75.2-113.3)[j]		(87.5-119.5)[h]	(78.4-99.6)[h]	
Hamstrings 300 deg/s	–	–	–	99.1	87.2	.565	102.6	104.4	.480	106.8	91.0	.085	103.9	97.0	.741
				(85.6-109.1)[c]	(78.6-102.6)[c]		(89.6-122.6)[i]	(82.8-110.7)[i]		(91.1-118.0)[j]	(71.0-116.3)[j]		(87.6-112.8)[h]	(83.0-121.1)[h]	
LSI hop injured/uninjured															
Single hop	–	–	–	94.9	97.4	.838	100.0	100.0	.678	97.1	100.0	.027[k]	99.6	100.9	.170
				(91.1-99.1)[d]	(83.0-102.1)[d]		(94.6-100.8)[l]	(96.6-102.9)[l]		(95.0-99.3)[m]	(97.4-103.0)[m]		(92.9-100.5)[i]	(96.9-104.1)[j]	
Triple hop	–	–	–	95.9	95.7	.673	99.5	99.3	.755	98.0	99.4	.137	96.0	100.4	.103
				(90.0-100.6)[d]	(86.8-99.6)[d]		(95.8-100.0)[l]	(95.5-100.0)[l]		(89.7-100.1)[d]	(95.2-102.9)[d]		(93.5-103.7)[n]	(96.7-109.6)[n]	
Side hop	–	–	–	96.3	95.0	.546	100.0	100.0	.690	96.9	101.7	.084	96.01	100.0	.256
				(82.1-102.6)[d]	(80.8-100.0)[d]		(94.9-102.8)[l]	(92.7-103.8)[l]		(74.5-101.7)[j]	(92.2-105.5)[j]		(91.9-100.0)[n]	(92.8-103.5)[n]	

[a]Since data were not normally distributed they are expressed as median (interquartile range) unless otherwise indicated. IKDC = International Knee Documentation Committee 2000, KOOS = Knee Injury and Osteoarthritis Outcome Score, ADL = activities in daily living, QoL = quality of life, VAS = visual analogue score, LSI = leg symmetry index, i/u = injured/uninjured. *=non-significant after Bonferroni-Holm correction for multiple testing.[b] Analysis based on 24 repair and 23 reconstruction patients.

[c] Analysis based on 24 repair and 21 reconstruction patients.

[d] Analysis based on n=21 repair and n=20 reconstruction patients.

[e] Analysis based on n=23 repair and n=20 reconstruction patients.

[f] Analysis based on 22 repair and 21 reconstruction patients.

[g] Analysis based on n=23 repair and n=21 reconstruction patients.

[h] Analysis based on n=23 repair and n=18 reconstruction patients.

[i] Analysis based on n=22 repair and n=19 reconstruction patients.

[j] Analysis based on n=21 repair and n=21 reconstruction patients.

[k] Nonsignificant after Bonferroni-Holm correction for multiple testing.

[l] Analysis based on n=24 repair and n=24 reconstruction patients.

[m] Analysis based on n=20 repair and n=22 reconstruction patients.

[n] Analysis based on n=22 repair and n=20 reconstruction patients.

Primary Outcome Measure: IKDC Subjective

The lower limit of the 2-sided 95% CI for the median IKDC subjective score of the dynamic augmented ACL suture repair group (86.2) fell within the prespecified noninferiority margin, confirming the null hypothesis of noninferiority of dynamic augmented ACL suture repair to ACL reconstruction (Figure 3).

No statistically significant difference was found between groups for the median IKDC subjective score at 2-year follow-up: 95.4 in the dynamic augmented ACL suture repair group and 94.3 in the ACL reconstruction group (*P* =0.902) (Tables 2 and 3).

Furthermore, no statistically significant differences were found between groups regarding changes in IKDC subjective scores at 3, 6, 9, 12 and 24 months postoperatively (Table 2).

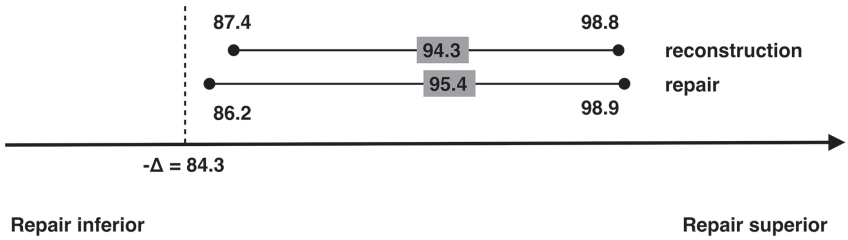

Figure 3. Noninferiority International Knee Documentation Committee (IKDC) subjective results at 2-year follow-up. Data are expressed as median with 95% confidence interval. Dotted line = median IKDC Subjective score of the ACL reconstruction group minus the clinically relevant difference (Δ) of 10 points = 84.3.

Table 3. Results of noninferiority test for International Knee Documentation Committee subjective score at 2-year follow-up after anterior cruciate ligament surgery with intention to treat analysis[a]

	n	2-Year Median (IQR)	95% CI	*P* Value
Repair	23	95.4 (80.5-100.0)	86.2-98.9	.902
Reconstruction	21	94.3 (86.5-98.9)	87.4-98.8	(*Z* = -0.123)

[a] IQR, interquartile range; ITT, intention to treat.

Secondary Outcome Measures

After Bonferroni-Holm correction for multiple testing, no statistically significant between-group differences were found at 3, 6, 9, 12 and 24 months postoperative for any of the secondary outcome measures except for the KOOS Other Symptoms score at 3 months postoperatively and the side-to-side difference of the instrumented Lachman test at 6 months postoperatively, with a median delta of ≤2mm in both groups (Table 2). Furthermore, no radiological signs of osteoarthritis were present at 1-year and 2-year follow-up.

Adverse events

Adverse events are presented in Table 4.

Table 4. Adverse events ≤2 year after anterior cruciate ligament (ACL) surgery[a]

	Repair (n = 23)	Reconstruction (n = 21)	*P Value*
Adverse events			.238
Ipsilateral ACL re-rupture	2 (8.7)	4 (19.0)	.663
Contralateral ACL rupture	2 (8.7)	0 (0.0)	.470
Repeat surgery	5 (20.8)	3 (14.3)	.669
Abnormal symptoms: pain, swelling, extension deficits	5 (20.8)	4 (19.0)	<.999
Other adverse events	3 (12.5)	1 (4.2)	.602

[a] Data are expressed as frequency (percentage).

Results showed 2 ipsilateral reruptures (8.7%) in the dynamic augmented ACL suture repair group and 4 ipsilateral reruptures (19.0%) in the ACL reconstruction group; 2 contralateral ACL ruptures (8.7%) occurred in the dynamic augmented ACL suture repair group versus none in the ACL reconstruction group. All patients with an ACL rerupture underwent revision ACL surgery with autologous ipsilateral patellar tendon without complications, using the prior tunnels. Overall, 5 repeat surgeries other than for revision ACL surgery took place in 4 patients from the dynamic ACL suture repair group (20.8%; 2 cyclops lesions, 2 cases of residual synovitis with suspected bacterial infection but negative intraoperative cultures, treated with adjuvant antibiotics and 1 extension deficit) and 3 in 3 patients from the ACL reconstruction group (14.3%; cyclops lesion). In 2 of these patients, the Ligamys implant was removed (5 months after the index surgery). In another 5 patients (20.8%) in the dynamic augmented ACL suture repair group and 4 patients (19.0%) in the ACL reconstruction group, symptoms of extension deficits, pain, and swelling occurred between 0 and 10 months postoperatively but disappeared spontaneously. In the dynamic ACL suture repair group, “other” adverse events entailed 1 patient who developed a traumatic tuberculum majus fracture during skiing and 1 patient with traumatic cervical spine fracture; no patients were awaiting hardware removal at 2-year follow-up.

DISCUSSION

The most important finding of this study is that dynamic augmented ACL suture repair was not inferior to ACL reconstruction in terms of subjective patient-reported outcomes as measured with the IKDC subjective score 2 years postoperatively; no statistically significant differences in IKDC subjective scores were found between groups. However, for reasons other than revision ACL surgery for rerupture, a higher yet nonsignificant number of related adverse events leading to repeat surgery was seen in the dynamic augmented ACL suture repair group within 2 years postoperatively.

As far as we are aware, the study by Schliemann et al. is the only RCT comparing contemporary (dynamic augmented) ACL suture repair with ACL reconstruction. [46] In line with the findings of our study, Schliemann et al. reported no differences between groups, which was consistent with earlier findings of those authors in a prospective cohort of patients treated with dynamic augmented ACL suture repair.[31, 46] At 1-year follow-up, Schliemann et al. found an IKDC subjective score of 85.7, which was slightly lower than the IKDC subjective score in our study at 1-year and 2-year follow-up (95.4 at both points).[46] Several prospective case series, authored by the developers of the dynamic augmentation technique, reported IKDC subjective scores of 94 to 100 obtained after dynamic augmented ACL suture repair at 1-year, 2-year and (in one pilot study with 10 patients) 5-year year follow-up. [6, 11, 22, 23, 30, 36] The median VAS scores for patient satisfaction in the current study, 9.3 at 1-year follow-up and 9.1 at 2-year follow-up, were comparable to those reported in literature, and no statistical difference was found between groups. [11, 23, 30, 36, 46] Furthermore, no statistical difference was found between groups in return to preinjury activity level 1 year and 2 years postoperatively; 58.3% in the ACL suture repair group and 42.9% in the ACL reconstruction group had returned to their previous Tegner level at 1 year, and 52.2% and 55.0%, respectively, had returned to their previous Tegner level at 2 years. As previously reported by other authors, the results for return to preinjury activity level in the ACL reconstruction group improved over time, with half of the patients returning to preinjury activity level at 2-year follow-up in both groups.[2] Thus, the IKDC subjective scores found in this study are consistent with those found in literature.

Although in this study only 2 implants were removed for medical reasons, the rate of repeat surgery for reasons other than rerupture was higher in the dynamic augmented ACL suture repair group when compared to the ACL reconstruction group (20.8% vs. 14.3% respectively), mainly because of swelling or extension deficit due to a cyclops lesion. Some

authors have reported an even higher rates of repeat surgery (up to 42%) because of implant removal for medical reasons (and not patient request), partly because of motion deficits (up to 23%) within 1 year postoperatively. [3, 6, 11, 19, 23, 29, 31, 36] This might be related to the necessity of scar formation for healing of the ruptured ACL, with this scar formation leading to the formation of a cyclops lesion and/or an extension deficit.[36] Furthermore, although young age and competitive sports activity, reflecting the population in this study, have been described as risk factors for both dynamic augmented ACL suture repair and ACL reconstruction, the rerupture rates found in this study are in line or lower than those rates described in literature (ranging from 7 to 15% and 8 to 28%, respectively).[3, 6, 11, 19, 21, 23, 29, 31, 32, 36, 37, 46, 57]

Midsubstance location of the ACL rupture also has been described as a risk factor for failure of dynamic augmented ACL suture repair.[21, 32] Interestingly, a difference was found between studies that used nonaugmented and static augmented suture repair techniques, which reported results of exclusively proximal ACL repairs, and studies that used dynamic augmented ACL suture repair, which reported results of proximal as well as central third repairs of the ruptured ACL. The results of some retrospective and prospective cohort studies of nonaugmented or static augmented ACL suture repair suggest that proximal ruptures of the ACL tend to have better clinical results compared with central or distal third ruptures.[9, 35, 53] However, in a prospective case control study that compared nonaugmented ACL suture repair with ACL reconstruction to treat proximal ACL ruptures, Achtnich et al. reported a statistical significant difference in rates of repeat surgery and failures, to the disadvantage of the ACL repair group.[1] Analyzing dynamic augmented ACL suture repair in more detail, Evangelopoulos et al. reported that contemporary dynamic augmented ACL suture repair alone for central or distal third ruptures of the ACL resulted in a high complication and failure rate (79%) at 2-year follow-up and addition of an ACL bridging collagen bioscaffold reduced complication and failure rate dramatically (to 9%).[13] Murray et al., after extensive research in animal model studies, recently reported no short term adverse events or differences compared with ACL reconstruction after application of a proprietary collagen bioscaffold for static augmented ACL suture repair in a prospective comparative clinical case series.[40] Hence, adding a collagen bioscaffold to ACL suture repair procedures might improve results of ruptures not only in the central or distal third of the ACL but also in the proximal third of the ACL, even for patients with younger age and high level of activity, as were included in this study.[13, 40] However, further research is necessary to investigate this possibility. Given that 16.7% of ruptures in this study were not located in the proximal third of the ACL and no bioscaffold was added to the procedure, this might have negatively affected the result of the dynamic augmented ACL suture repair group.

Limitations

This study has limitations that have to be addressed. First, the sample size is too small to draw conclusions on potential differences in rerupture rate between groups. However, the sample size is large enough to sufficiently confirm the null hypothesis.

Second, in contrast to the present study, historical ACL suture repair was performed nonaugmented or with static augmentation, patients were treated with arthrotomy and immobilized for several weeks postoperatively, and tear location seemed to play a role; studies of these historical techniques reported good to excellent short-term but deteriorating mid- to long-term outcome.[12, 14, 48, 49, 53] The present study reports short-term outcomes, and by itself this is not sufficient to evaluate the utility of the dynamic augmented ACL suture repair technique as treatment modality for acute ACL ruptures. More high-quality studies with longer follow-up are needed. Nevertheless, this is the first independent RCT examining contemporary (dynamic) augmented ACL suture repair compared with ACL reconstruction, and its short-term results might give some direction to future research.

Third, although 3 patients were treated with dynamic augmented ACL suture repair before the study, a longer learning curve for the ACL suture repair procedure has to be considered.

Fourth, for practical reasons, neither the patient nor the assessors were blinded, which might have introduced some form of bias.

Fifth, although no differences between groups were found, the variation in KOOS and IKDC subjective scores between patients within both groups at baseline was high. The questionnaires ask for symptoms in the past 4 weeks, a period which in this study can overlap the preinjury and the injured state of the knee. It is probable that patients interpreted the questionnaires in a different manner, answering as to the state of the knee before or after the injury. In future research, to compare postoperative results to the preinjury state of the knee between patients within groups, it might be better to ask for symptoms in the 4 weeks before injury explicitly.[23]

Sixth, no gold standard criterion is available for determining an appropriate noninferiority margin.[17] The most common approach in treatment outcome studies is to set a margin based on what is considered ”clinically unimportant”.[16, 45] For noninferiority studies, some advocate an additional per protocol analyses to compensate for protocol violation in order to demonstrate noninferiority from a more conservative perspective compared to an ITT analysis.[43] In the dynamic augmented ACL suture repair group, the surgical removal of the dynamic augmentation device in two patients could be considered a protocol violation. However, is has been reported that the braid of the dynamic augmentation device gradually loses tension, and therefore function, in the first months postoperatively.[3] Given that the 2 patients who were subject to protocol violations had their dynamic augmentation device

removed 5 months postoperatively, it is unlikely that this affected their results at 2-year follow-up.

CONCLUSION

These results have shown that the effectiveness of dynamic augmented ACL suture repair is not inferior to that of ACL reconstruction in terms of subjective patient-reported outcomes as measured with the IKDC subjective score 2 years postoperatively. However, for reasons other than revision ACL surgery for rerupture, a higher number of related adverse events leading to repeat surgery were seen in the dynamic augmented ACL suture repair group within 2 years postoperatively.

CLINICAL RELEVANCE

Although no high-level evidence with long-term follow-up exists, and the repeat surgery rate seems rather high, dynamic augmented ACL suture repair might be considered as a viable treatment option for patients with an acute ACL rupture.

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CHAPTER 7

Acute Anterior Cruciate Ligament Rupture: Repair or Reconstruction? Five-Year Results of a Randomized Controlled Clinical Trial

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ABSTRACT

Background: High-level evidence for short-term outcomes of contemporary anterior cruciate ligament (ACL) suture repair (ACLSR) in comparison with those of ACL reconstruction (ACLR) is scarce. High-level evidence for mid- and long-term results is lacking, whereas outcomes of ACLSR in several historical studies were shown to deteriorate at midterm follow-up after initial good short-term outcomes.

Hypothesis: Contemporary ACLSR is noninferior to ACLR in the treatment of acute ACL rupture in terms of patient self-reported outcomes at 5 years postoperatively.

Study Design: Randomized controlled trial; Level of evidence, 1.

Methods: A total of 48 patients were enrolled in the study and, after stratification and randomization, underwent either dynamic augmented (DA) ACLSR or anatomic single-bundle ACLR. The primary outcome measure was the International Knee Documentation Committee 2000 (IKDC) subjective score (IKDCs). Furthermore, the Knee injury and Osteoarthritis Outcome Score (KOOS), Tegner Activity Scale score (TAS), visual analog scale score for satisfaction (VASs), IKDC physical examination score (IKDCpe), limb symmetry index for quadriceps (LSIq) and hamstrings (LSIh) strength and jump test battery (LSIj), Kellgren-Lawrence grade of osteoarthritis (OA), and rate of adverse events were recorded. Analyses were based on an intention-to-treat principle.

Results: The lower limit of the 2-sided 95% CI for the median IKDCs of the DA ACLSR group (n = 23; 75.9) was lower than the prespecified noninferiority margin (n = 21; 86.6). Therefore, the null hypothesis was rejected. However, the upper limit of the 2-sided 95% CI of the DA ACLSR group (100.0) was higher than the median IKDCs of the ACLR group (96.6), rendering the result for noninferiority inconclusive. No statistical difference was found between groups for median IKDCs (repair, 90.2; reconstruction, 96.6). Furthermore, no statistically significant differences were found for any of the secondary outcome measures for the DA ACLSR compared with the ACLR group: KOOS Symptoms, 92.9 versus 96.4; KOOS Pain, 100 versus 97.2; KOOS Activities of Daily Living, 100 versus 100; KOOS Sport and Recreation, 85.0 versus 100; TAS score, 7.0 versus 6.5; VASs, 9.2 versus 8.7; IKDCpe, 81.8% versus 100%; LSIq, ≥91.6 versus ≥88.2; LSIh, ≥95.1 versus ≥90.7; LSIj, ≥94.2 versus ≥97.6; OA grade 0, 90.9% versus 77.8%; clinical ACL failure rate, 20.8% versus 27.2%; and repeat surgery rate, 37.5% versus 20.0%, respectively.

Conclusion: It remains inconclusive whether the effectiveness of DA ACLSR is noninferior to that of ACLR in terms of subjective patient-reported outcomes as measured using the IKDCs. Although DA ACLSR may be a viable treatment option for patients with acute ACL rupture, caution must be exercised when considering this treatment for young, active patients, corresponding to the present study population.

INTRODUCTION

There has been renewed interest in the concept of contemporary anterior cruciate ligament (ACL) suture repair (ACLSR) rather than ACL reconstruction (ACLR) using a tendon graft for surgical treatment of the ruptured ACL. The amount of literature on ACLSR has rapidly increased in the past decade, and good to excellent short-term outcomes have been reported.[24, 53] However, high-level evidence for short-term outcomes of contemporary ACLSR in comparison with those of ACLR is scarce, and such evidence for mid- to long-term outcomes is lacking.[10,23,24,34,41] While the few randomized controlled trials (RCTs) on contemporary ACL suture techniques have reported good to excellent short-term outcomes, there is fear of history repeating itself, as initial satisfactory short-term results of several historical studies on ACLSR were reported to deteriorate at midterm follow-up.[10, 23, 34, 41, 46] It was reported that this deterioration might have been dependent on ACL rupture location, the quality of the ruptured ACL tissue, and the lack of augmentation of the suture-repaired ACL.[25, 48, 50] Therefore, there is a need for more randomized controlled studies with an adequate follow-up period, investigating patient-reported outcome measures and clinical stability testing to compare contemporary ACLSR techniques with ACLR.[10, 24, 46, 53]

In 2019, Hoogeslag et al[23] reported that contemporary dynamic augmented (DA) ACLSR was noninferior to single-bundle ACLR with a hamstrings autograft in terms of subjective patient-reported outcome as measured using the International Knee Documentation Committee 2000 (IKDC) subjective score (IKDCs) and that there were no statistically significant differences in other patient-related, clinical, and radiological outcomes at short-term (2-year) follow-up. This study presents the 5-year outcomes for patients included in this RCT.

MATERIALS AND METHODS

The materials and methods have been extensively described by Hoogeslag et al.[23] An institutional review board (No. NL50116.044.14; P14-26)–approved RCT was conducted at the Centre for Orthopaedic Surgery OCON, the Netherlands. In the study period between January 2015 and March 2016, we enrolled patients who were 18 to 30 years of age; visited the outpatient clinic; had a proven primary ACL rupture confirmed by means of history, physical examination, and magnetic resonance imaging; had an indication for ACLR surgery; could be treated with surgery within 21 days after injury; and had a score of 5 to 10 on the Tegner Activity Scale (TAS) (Table 1).[49] Inclusion in the study was independent of ACL rupture

location. Exclusion criteria were concomitant ligamentous lesions, a history of contra- or ipsilateral knee surgery, meniscal lesions needing surgical repair and full-thickness cartilage lesions, and osteoarthritis seen on the preoperative (weightbearing) radiographs.

The details of the inclusion, stratification (preinjury TAS score [moderate TAS score, 5-7; high TAS score, 8-10]), and randomization (blocks of varying sizes [sealed envelope, computer-generated schedule; block size n = 2 and n = 4]) to undergo either DA ACLSR or ACLR with a tendon graft have been previously reported.[23] Patients were not blinded to treatment.

Surgical Procedure

The surgical procedures have been extensively described by Hoogeslag et al.[23] DA ACLSR was performed within 3 weeks after injury, and ACLR was performed within 2 weeks after patients met the preoperative criteria for functional recovery of the knee and leg.[52] If patients who were planned to undergo ACLR did not meet these preoperative criteria at baseline, they were reassessed at a later stage and meanwhile continued preoperative rehabilitation with a sports physical therapist. One experienced ACL surgeon (R.A.G.H.) performed all surgeries.

Anterior Cruciate Ligament Suture Repair. ACLSR was performed using the dynamic intraligamentary stabilization technique (Ligamys; Mathys Medical) as described by Eggli et al[8] (Figure 1). The Ligamys braid was tensioned to 80 N at 0° of knee flexion (Figure 1), and microfracturing of the notch was performed in and near the femoral ACL attachment.[25]

Anterior Cruciate Ligament Reconstruction. Anatomic ACLR was performed using a single-bundle all-inside ipsilateral semitendinosus technique (Arthrex).[37] A mini-incision technique at the posterior side of the knee was used to harvest the tendon, which was then quadrupled.[44] Using a retrograde drill, we prepared independent tibial and femoral sockets (Flipcutter; Arthrex).[37] The graft was tensioned with the knee at 0° of knee flexion. Graft tension was adjusted under arthroscopic view if necessary.

Postoperative Rehabilitation. Postoperatively, patients who underwent DA ACLSR received a long leg splint locked in extension for the first 5 days, and patients who underwent ACLR were allowed full range of motion as tolerated directly. Both groups received an otherwise identical, structured, criterion-based rehabilitation protocol and were guided by their own sports physical therapist accordingly.[52]

Table 1. Summary of Baseline Characteristics and ACL Rupture Characteristics[a]

	Repair, n =24		Reconstruction, n =24		*P* Value
Sex					.731
Male	19	(79.2)	18	(75)	
Female	5	(20.8)	6	(25)	
Age, y	21.0	(18.0-27.0)	22.0	(19.3-25.0)	.693
Injured side					.247
Left	9	(37.5)	13	(54.2)	
Right	15	(62.5)	11	(45.8)	
BMI	23.0	(21.0-24.5)	23.3	(22.1-24.4)	.445
IKDC Subjective score	72.4	(49.1-95.2)	59.8	(39.0-100.0)	.438
KOOS					
Symptoms	96.0	(41.8-100.0)	54.0	(64.0-94.6)	.261
Pain	100	(62.5-100.0)	62.5	(50.8-100.0)	.095
ADL	99.5	(66.8-100.0)	73.5	(57.0-100.0)	.245
Sport and Recreation	97.5	(17.5-100.0)	27.5	(6.3-100.0)	.194
QoL	97	(44.0-100.0)	53.5	(20.5-100.0)	.208
TAS score	8.0	(7.0-9.0)	8.5	(7.0-9.0)	.893
TAS score stratification					.771
Intermediate	11	(45.8)	10	(41.7)	
High	13	(54.2)	14	(58.3)	
ACL rupture location					
Proximal third	20	(83.3)		—	
Central third	3	(12.5)		—	
Distal third		1 (4.2)		—	
ACL rupture bundle					
1 strand	3	(12.5)		—	
2 bundles	10	(41.7)		—	
≥ 3 strands	11	(45.8)		—	
ACL rupture sheath					
Completely intact	3	(12.5)		—	
≥50% intact	16	(66.7)		—	
<50% intact	5	(20.8)		—	

[a]Since data were not normally distributed, they are expressed as median (interquartile range) or frequency (%). ACL, anterior cruciate ligament; ACL, Activities in Daily Living; BMI, body mass index; IKDC, International Knee Documentation Committee 2000; KOOS, Knee injury and Osteoarthritis Outcome Score; QoL, Quality of Life; TAS, Tegner Activity Scale; –, not applicable

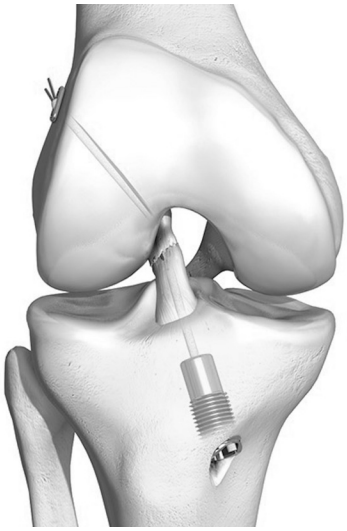

Figure 1. Dynamic augmentation of the ruptured anterior cruciate ligament (ACL). ACL suture repair augmented with intraligamentary braid with cortical button fixation on the femoral side and additional elastic link (a spring-in-screw mechanism) on the tibial side (Reprinted with permission of Hoogeslag et al.).[24]

Outcome Measures

Patients were evaluated at the 5-year follow-up using patient-reported outcome measures and physical and radiological examination. Similar to our previous study, the primary outcome measure was the IKDCs at the 5-year follow-up.[23] The IKDCs is validated in Dutch and measures symptoms and functional limitations for a variety of knee disorders, including ligamentous injuries (range, 0- 100; worst to best).[20,29,30]

Secondary outcome measures included patient-reported, clinical, and radiological outcome measures as well as clinical ACL failure (a combination of subjective instability, findings at physical examination, and/or graft rupture) and repeat surgery rates and rates of other complications and non–knee related adverse events at the 5-year follow-up: TAS (range, 0-10; low physical activity to high physical activity), visual analog scale (VAS) for satisfaction (range, 0-10; unsatisfied to very satisfied), Knee injury and Osteoarthritis Outcome Score (KOOS; range, 0-100; worst to best), IKDC physical examination score (range, A-D; best to worst) including instrumented Lachman test (Rolimeter), limb symmetry index (LSI) for jump tests (single-leg hop and hold, side hop, and triple hop for distance) and for isokinetic quadriceps and hamstrings strength (peak torque at 60 deg/s, 180 deg/s, and 300 deg/s; isoforce dynamometer; TUR), and signs of osteoarthritis scored on the anteroposterior weightbearing and lateral radiographs using the Kellgren-Lawrence score (0-4; no

osteoarthritis to severe osteoarthritis).[3,5,18,29,32] Two independent experienced sports physical therapists performed the assessments in the orthopaedic department's outpatient clinic. Assessors were not blinded for the patients' treatment allocation for practical reasons.

Statistical Analysis

A detailed description of the statistical analysis has been previously reported.[23] Sample size was calculated based on 1-sided noninferiority of ACLSR to ACLR for the IKDCs, standard deviation was set at 9, and the clinically relevant difference was set at 10.[4,30] A sample size of 20 patients in each study group was required to achieve a statistical power of 90% and an alpha of 5%. Twenty-four patients per group were included (48 total) to allow for a lost-to-follow-up rate of 20%. Noninferiority of DA ACLSR to ACLR regarding the primary outcome was assessed using an intention-to-treat analysis (ie, by including patients who completed the IKDCs questionnaire at the 5-year follow-up).[43]

DA ACLSR was considered noninferior to ACLR if the lower limit of the 2-sided 95% CI of the IKDCs of the DA ACLSR group was within the margins of clinically significant difference (of 10 points) of the median IKDCs of the ACLR group. As data were not normally distributed, the 95% CI around the median IKDCs at the 5-year follow-up was calculated per group using the Gardner and Altman formula (https://www.openepi.com/CIMedian.htm).

Descriptive results are presented as median (interquartile range [IQR] or frequency [percentage]) for continuous and categorical variables, respectively. The Mann-Whitney-Wilcoxon test was used to investigate the difference between groups for continuous variables. The chi-square test was used to test for significant differences between groups for categorical variables. The related- samples Wilcoxon signed rank test was used to investigate the difference within groups between the 2-year and 5-year follow-up. The change of IKDC scores within groups between the 2-year and 5-year follow-up was calculated, and an independent t test was used to investigate if this was different between groups.

Statistical analyses were performed using SPSS Version 22.0 (IBM Corp), and the level of significance was set to $<.05$.

RESULTS

Of the 375 patients who underwent primary ACLR, 323 patients did not meet the inclusion criteria, 3 declined to participate, and 1 was excluded preoperatively because of the need for a meniscal suture repair, leaving 48 patients who were included in the study.[24] During the 5-year follow-up, 1 patient in the ACLSR group and 3 patients in the ACLR group were lost to follow-up (Figure 2).

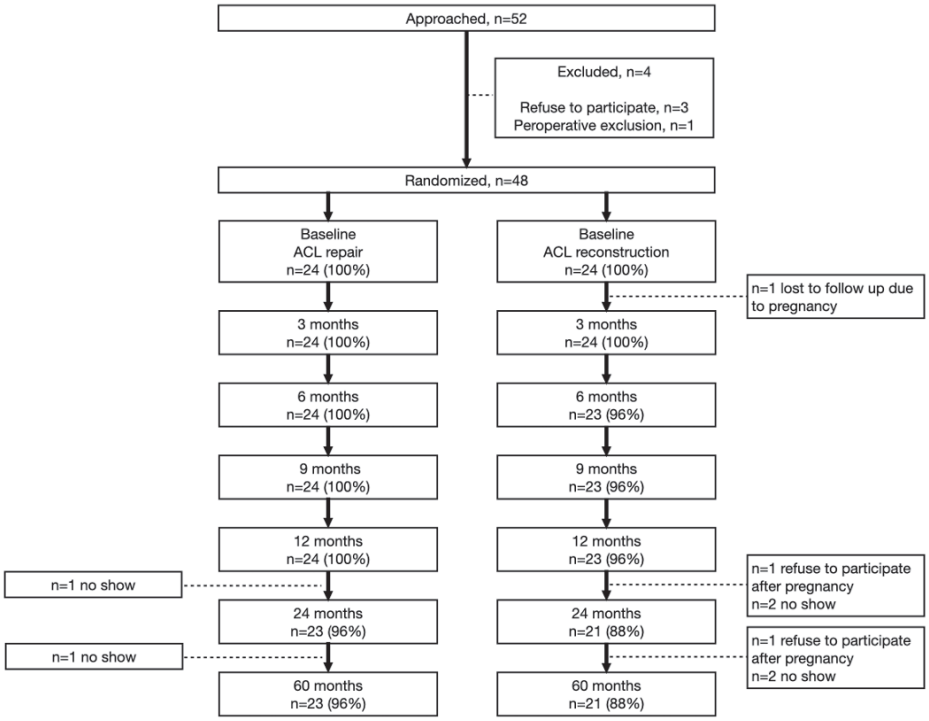

Figure 2. Flowchart of inclusion and randomization of participants. ACL, anterior cruciate ligament.

Primary Outcome Measure: IKDCs

The lower limit of the 2-sided 95% CI for the median IKDCs of the DA ACLSR group at the 5-year follow-up (75.9) was lower than the prespecified noninferiority margin (86.6). Therefore, the null hypothesis of noninferiority of the DA ACLSR was rejected (Table 2, Figure 3). However, the upper limit of the 2-sided 95% CI of the DA ACLSR group at the 5-year follow-up (100.0) was higher than the median IKDCs of the ACLR group (96.6). Therefore, the results were inconclusive, and DA ACLSR was not considered inferior to ACLR (Table 2, Figure 3). No statistically significant difference in the median IKDCs at the 5-year follow-

up was found between groups (ACLSR, 90.2; ACLR, 96.6; *P* = .571) (Tables 2 and 3). The difference in IKDCs between the 2-year and 5-year follow-up was 1.2 ± 11.0 for the ACLSR group and 0.8 ± 8.3 for the ACLR group, and this was not statistically significant between groups (*t*(39) = 0.629; *P* = .533).

Table 3. Results of non-inferiority for International Knee Documentation Committee 2000 subjective scores at five-year follow-up after anterior cruciate ligament surgery[a]

ITT Analysis	n	Median (IQR)	95% CI	*P* Value
Repair	23	90.2 (75.9–100.0)	75.9–100.0	.571
Reconstruction	21	96.6 (86.8–98.9)	88.5–98.9	(Z .567)

[a] IQR, interquartile range; ITT, intention-to-treat.

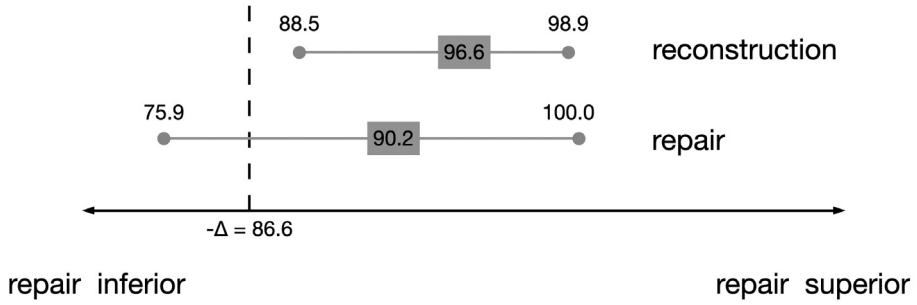

Figure 3. Noninferiority as per International Knee Documentation Committee 2000 (IKDC) subjective scores at 5-year follow-up. Data are expressed as median with 95% CI. The dotted line indicates the median IKDC subjective score of the anterior cruciate ligament reconstruction group minus the clinically relevant difference (Δ) of 10 points (86.6).

Secondary Outcome Measures

No statistically significant differences were found between groups at the 5-year follow-up in any of the secondary outcome measures (Table 3).

Adverse Events

Several adverse events were reported between the 2- and 5-year follow-up, in addition to those reported between index surgery and the 2-year follow-up (Table 4).[24] Three ipsilateral clinical failures occurred in the DA ACLSR group versus 2 in the ACLR group. All patients with clinical failure underwent single-stage revision ACL surgery using autologous ipsilateral patellar tendon without complications, using the previous tunnels. One contralateral ACL rupture occurred in the DA ACLSR group and none in the ACLR group.

Table 3. Primary and Secondary Outcome Measures in the Dynamic Augmented Anterior Cruciate Ligament Suture Repair and Anterior Cruciate Ligament Reconstruction Groups at 5-year Follow-up[a]

	5-y Follow-up		
	Repair	Reconstruction	*P* Value
IKDC subjective score	90.2 (75.9–100.0)[b]	96.6 (86.8–98.9)[b]	.571
KOOS			
Symptoms	92.9 (85.7–96.4)[b]	96.4 (89.3–100.0)[b]	.172
Pain	100.0 (94.4–100.0)[b]	97.2 (94.4–100.0)[b]	.722
ADL	100.0 (97.1–100.0)[b]	100.0 (100.0–100.0)[b]	.279
Sport and Recreation	85.0 (75.0–100)[b]	100.0 (86.3–100.0)[b]	.138
QoL	75.0 (50.0–100.0)[b]	81.3 (71.9–100.0)[b]	.125
TAS	7.0 (4.0–9.0)[c]	6.5 (4.0–8.8)[c]	.891
Active at preinjury TAS level	7 (35.0)[c]	9 (39.1)[c]	.780
VAS satisfaction score	9.2 (6.9–9.8)[b]	8.7 (7.1–9.7)[b]	.645
IKDC physical examination score			.134
A	18 (81.8)[d]	20 (100.0)[d]	
B	3 (13.6)[d]	0 (0.0)[d]	
C	1 (4.5)[d]	0 (0.0)[d]	
D	0 (0.0)[d]	0 (0.0)[d]	
Lachman delta, mm	1.0 (0.0–2.0)[e]	1.0 (0.0–1.0)[e]	.491
LSI force ratio, i/u			
Quadriceps 60 deg/s	91.6 (82.2–107.5)[f]	91.1 (84.7–101.2)[f]	.648
Quadriceps 180 deg/s	95.1 (85.3-107.2)[f]	93.2 (81.8-102.0)[f]	.259
Quadriceps 300 deg/s	93.4 (83.7-102.3)[f]	88.2 (82.1-97.2)[f]	.377
Hamstrings 60 deg/s	95.1 (83.7-104.5)[f]	94.7 (86.6-106.8)[f]	.692
Hamstrings 180 deg/s	96.3 (84.7-102.7)[f]	90.7 (83.9-98.4)[f]	.428
Hamstrings 300 deg/s	97.5 (90.8-108.5)[f]	100.7 (84.5-109.3)[f]	.493
LSI hop, i/u			
Single hop	97.9 (91.8-103.8)[g]	98.3 (95.0-103.1)[g]	.656
Triple hop	94.2 (90.0-103.9)[g]	98.5 (92.9-102.1)[g]	.265
Side hop	97.2 (90.3-105.4)[h]	97.6 (88.6-106.4)[h]	.778
KL			.247
0	20 (90.9)[i]	14 (77.8)[i]	
1	2 (9.1)[i]	4 (22.2)[i]	
2	0 (0.0)[i]	0 (0.0)[i]	
3	0 (0.0)[i]	0 (0.0)[i]	
4	0 (0.0)[i]	0 (0.0)[i]	

[a] Since data were not normally distributed, they are expressed as median (interquartile range) or frequency (%). ADL, Activities in Daily Living; i/u, injured/uninjured; IKDC, International Knee Documentation Committee 2000; KL, Kellgren–Lawrence osteoarthritis score; KOOS, Knee injury and Osteoarthritis Outcome Score; LSI, leg symmetry index; QoL, Quality of Life; TAS, Tegner Activity Scale; VAS, visual analogue scale.
[b] Analysis based on 23 patients with repair and 21 patients with reconstruction.
[c] Analysis based on 23 patients with repair and 20 patients with reconstruction.
[d] Analysis based on 22 patients with repair and 20 patients with reconstruction.
[e] Analysis based on 22 patients with repair and 19 patients with reconstruction.
[f] Analysis based on 20 patients with repair and 17 patients with reconstruction.
[g] Analysis based on 20 patients with repair and 16 patients with reconstruction.
[h] Analysis based on 19 patients with repair and 16 patients with reconstruction.
[i] Analysis based on 22 patients with repair and 18 patients with reconstruction.

Furthermore, repeat surgeries other than for revision ACL surgery took place in 4 patients from the DA ACLSR group (cyclops lesion, ACL rerupture stump impingement, medial meniscal tear, and recurrent pain) and 1 patient in the ACLR group (snapping lateral meniscus). No patients were awaiting hardware removal at the 5-year follow-up.

Last, 4 non–knee related adverse events were reported in the DA ACLSR group (1 renal insufficiency and subsequent kidney transplant; 1 concern of pain at the tibial button after contralateral ACLR; 1 contralateral combined posterior cruciate ligament and posterolateral corner injury; and 1 hernia nucleus pulposus, which was symptomatic at the time of the 5-year follow-up) and 1 in the ACLR group (symptomatic shoulder instability).

Table 4. Adverse Events ≤5 Years after ACL Surgery.[a]

	2-y Follow-up[23]			5-year Follow-up		
	Repair	Reconstruction	*P* Value	Repair	Reconstruction	*P* Value
Adverse events			.238			.330
Ipsilateral clinical ACL failure	2 (8.7)[b]	4 (19.0)[b]	.663	5 (20.8)[d]	6 (27.2)[d]	.731
Contralateral ACL rupture	2 (8.7)[b]	0 (0.0)[b]	.470	3 (13.0)[e]	0 (0.0)[e]	.094
Repeat surgery	5 (20.8)[c]	3 (14.3)[c]	.669	9 (37.5)[f]	4 (20.0)[f]	.205
Abnormal symptoms: pain, swelling, extension deficits, donor site morbidity	5 (20.8)[c]	4 (19.0)[c]	>.999	6 (26.1)[b]	7 (33.3)[b]	.599
Other non-knee-related adverse events	3 (12.5)[d]	1 (4.2)[d]	.602	7 (29.2)[f]	1 (5.0)[f]	.038

[a] Data are expressed as frequency (%). Data on adverse events is based on different numbers of patients in each group, for instance, if a patient had a contralateral clinical ACL failure within 2 or 3 years postoperatively but was lost to follow-up at 5 years. ACL, anterior cruciate ligament.
[b] Analysis based on 23 patients with repair and 21 patients with reconstruction.
[c] Analysis based on 24 patients with repair and 21 patients with reconstruction.
[d] Analysis based on 24 patients with repair and 22 patients with reconstruction.
[e] Analysis based on 23 patients with repair and 20 patients with reconstruction.
[f] Analysis based on 24 patients with repair and 20 patients with reconstruction.

DISCUSSION

The most important finding of this study was that, because of the wide CI around the median IKDCs of the DA ACLSR group, the results were inconclusive regarding whether DA ACLSR is noninferior to ACLR in terms of the IKDCs 5 years postoperatively. Nevertheless, no statistically significant difference for the IKDCs or for any of the secondary outcomes between groups was found.

To the best of our knowledge, this is the first RCT reporting outcomes of contemporary ACLSR in comparison with those of ACLR at a midterm (5-year) follow-up. Only a few case series on this topic with a 5-year follow-up (or longer) have been published. Some retrospective case series on nonaugmented and static augmented ACLSR have reported outcomes comparable with those reported in the present study.[7,22,27] Furthermore, in a prospective pilot study of 10 patients after DA ACLSR, Eggli et al[9] reported a median IKDCs of 98.9 with a range of 79.3 to 100 at the 5-year follow-up. In a prospective case series of 57 patients after DA ACLSR, Ahmad et al[1] reported a median IKDCs of 94.0 with a range of 63.2 to 100.0 at the 6-year mean follow-up. Last, in a prospective case series of 65 patients after DA ACLSR, Kosters et al[33] reported a mean IKDCs of 90.0 at the 5-year follow-up; however, they reported neither standard deviation nor range. Moreover, the median IKDCs in the present study at the 5-year follow-up is comparable with that reported in other studies on ACLSR with shorter follow-up periods as well as with that reported for ACLR in comparative studies.[24,34,41] No comparative study between contemporary ACLSR and ACLR with midterm outcome is available to compare any of the outcome measures reported in the present study.[24] Thus, overall, the median outcome for the IKDCs for the ACLSR group in the present study seems to be on par with those reported in the literature for both ACLSR and ACLR at short- and midterm follow-up.

Although the reported failure, complication, and repeat surgery rates after contemporary DA ACLSR vary widely and some authors report these to be unacceptably high, the results in the present study fell well within the limits of those reported in the literature for contemporary ACLSR.[24,28,39,42] Furthermore, the reported clinical failure rates for both groups (DA ACLSR, 20.8%; ACLR, 27.2%) were consistent with those reported in the literature for ACLR in young and active patients, reflecting the population of the present study.[19] For ACLR, Getgood et al[15] and Mohtadi et al[40] reported clinical failure rates of 40% and 26% in their RCTs, respectively, and Wiggins et al[55] reported ACL graft rupture rates between 6.3% and 34.2% in a systematic review. Moreover, Rousseau et al[47] reported a 39% overall complication rate and 28% repeat surgery rate within a 2- year follow-up period after ACLR in a population of 811 patients, which are also similar to the results for both groups in the present study. Last, consistent with our results, several other comparative studies between contemporary ACLSR and ACLR with shorter follow-up periods reported no differences in adverse events between groups.[24,34,41] Therefore, the clinical failure, complication, and repeat surgery rates reported in the present study seem to be on par with those reported in the literature.

In the present study, although there was no statistically significant difference between groups at the 5-year follow-up and within groups between the 2-year and 5-year follow-up, the lower limits of the IQR and 95% CI for the median IKDCs in the DA ACLSR group decreased more than those in the ACLR group over time; this caused the null hypothesis to be rejected.[23] This finding brings to mind several historical ACLSR studies that had good short-term outcomes but deteriorating midterm outcomes. In 1976, Feagin and Curl[13] reported initial good to excellent outcomes at the 2-year follow-up of nonaugmented ACLSR of mainly proximally ruptured ACLs in a young and athletically active population, but a clinical failure rate >50% at the 5-year follow-up. These results were echoed in several other studies, and although it was subsequently proposed that proximal ACL rupture location with good tissue quality would yield better results, the discussion about patient selection criteria came too late, which ultimately led to the abandonment of ACLSR in favor of ACLR in the late previous century.[11,14,31,38,48,50] Recently, patient selection criteria for contemporary ACLSR have been proposed, and younger age (which may be a proxy for activities that are strenuous on the knee), (pursuit of) higher activity level, midsubstance ACL rupture location, lack of integrity of the ruptured ACL tissue and synovial sheath, and prolonged time from injury to surgery have been reported to negatively influence the outcomes of contemporary ACLSR techniques.[2,12,21,27,35,51,54] Except for timely operative treatment, none of the above factors were considered when including patients in the present study; included patients were young and athletically active, their inclusion was independent of ACL rupture location (although most patients had a proximal ACL rupture with <50% retraction of the synovial sheath), and the majority had a multilacerated tibial ACL remnant.[23] Thus, this might have negatively influenced the results for DA ACLSR in the present study. Nevertheless, no statistically significant differences were found for any of the reported outcome measures between groups. Moreover, patient satisfaction was high, and side-to-side differences assessed with the instrumented Lachman test were <3 mm in both groups.

The addition of a collagen bioscaffold to DA ACLSR in midsubstance ACL ruptures was reported to decrease complication rates drastically (from 79% to 9% at the 2-year follow-up).[12] Recently, an RCT by Murray et al[41] reported that the outcomes of ACLSR with the addition of a proprietary bioscaffold were noninferior to those of ACLR at the 2- year follow-up; the patients in the ACLSR group predominantly had nonproximal ACL ruptures. Furthermore, a recent RCT reported that the addition of anterolateral corner reconstruction could protect the reconstructed ACL, with a significant and clinically relevant reduction in failure rate.[15] It has now been proposed that the addition of anterolateral corner reconstruction in ACLSR may add rotational stability and reduce complication rates in

high-risk patients as well.[6,26] However, further research is necessary to investigate these possibilities.

Limitations

To our knowledge, this is the first independent RCT comparing contemporary DA ACLSR with ACLR reporting the outcomes at the 5-year follow-up. Although by itself this is not sufficient to evaluate the utility of DA ACLSR as a treatment modality for acute ACL ruptures, our results could provide direction to future research. Nevertheless, this study had several limitations, and these have been extensively described by Hoogeslag et al.[23] Some of these limitations are worth revisiting explicitly. First, most importantly, the sample size was large enough to reject the null hypothesis, but it had insufficient power to enable us to draw conclusions on potential differences in secondary outcomes between groups.

Second, there was no standard criterion to determine an appropriate noninferiority margin.[17] In treatment outcome studies, a noninferiority margin is commonly set based on what is considered clinically relevant.[16,45] Therefore, with a reported minimal clinically relevant difference of 8.8 to 15.6 points for the IKDCs, the clinically relevant difference was set at 10, and the standard deviation was set at 9.[4, 30, 36]

Third, although no differences between groups were found, the variation in IKDCs and KOOS within both groups at baseline was high. This was probably caused by the nature of the questionnaires, which ask for symptoms in the past 4 weeks, versus the nature of the study, in which baseline characteristics were measured well within 3 weeks after the knee injury. Therefore, since the questionnaires overlap the preinjury and injured state of the knee, it is probable that patients interpreted the questionnaires in a different manner. The (very) high IQR for the KOOS Sport and Recreation subgroup substantiates this assumption. In future studies on acute ACL injuries, it might be better to ask for symptoms in the 4 weeks before the injury explicitly.

CONCLUSION

The results of the present study were inconclusive regarding the noninferiority of DA ACLSR to ACLR in terms of subjective patient-reported outcomes as measured using the IKDCs.

CLINICAL RELEVANCE

Although DA ACLSR may be a viable treatment option for patients with acute ACL rupture, caution must be exercised when considering this treatment for young, active patients, corresponding to the present study population.

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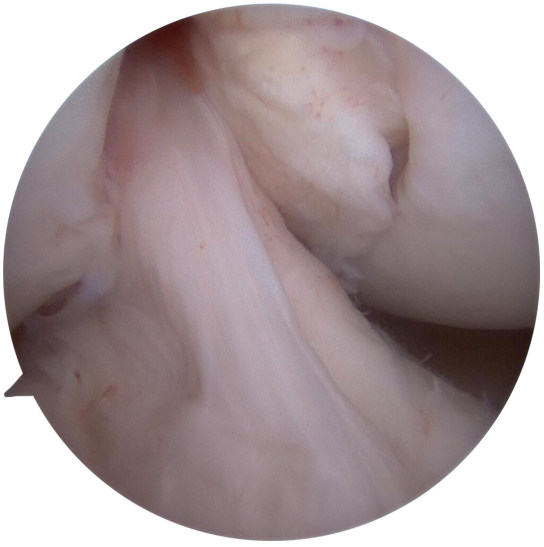

CHAPTER 8

General Discussion

In this thesis, the literature on clinical outcomes of modern anterior cruciate ligament (ACL) suture repair (ACLSR) techniques was systematically reviewed, the role of modern augmentation techniques in ACLSR was investigated, and the early and midterm outcomes of modern DA ACLSR were assessed in relation to the current surgical gold standard, ACL reconstruction (ACLR). The general discussion in this chapter reflects on the papers presented in this thesis, particularly how they might help to answer the question of the role of modern ACLSR in the treatment of acute ACL injury and to determine directions for future research.

Clinical outcomes of modern ACLSR techniques

As mentioned in the introduction, historical ACLSR was abandoned in favour of ACLR in the late 20th century. However, since both historical ACLSR and the current treatment options (non-operative and ACLR) fail to fulfil the overall purpose of treatment of patients with ACL injury, researchers have regained interest in ACLSR in a quest to improve treatment of such patients[24, 58].

To assess the outcomes of modern ACLSR, a systematic review (SR) of the literature was conducted (**Chapter 2**)[24]. High heterogeneity was found in the characteristics of the studies, and overall, the level and quality of evidence was low, to the extent that no meta-analysis of the data was possible. After the SR in this thesis, which found only a small number of papers on the clinical outcome of modern ACLSR since 2014, there has been a surge of SRs on this topic, with several different perspectives and research questions[21]. While this surge of reviews reflects the increasing interest on the topic, it also underlines the current quest of the orthopaedic community to (re)define the role of modern ACLSR in the treatment of acute ACL rupture. The results of other recently published SRs are largely in line with the findings of the SR in this work, indicating that the overall level and quality of evidence is rather low.

In the SR in this thesis (**Chapter 2**), good to excellent subjective outcomes were reported. Nevertheless, a high variability was found in the reported failure rate, rate of other complications and the repeat surgery rate. The reported failure rate ranged from 0% to 27% (with one outlier at 49%)[24]. While these findings may give the impression that the results of ACLSR are ambiguous, this variability may be due to several factors, such as patient selection, ACL rupture characteristics, ACLSR technique, and the definition of clinical failure after ACL surgery (which can be subject to debate)[2, 13, 20, 24, 32]. For ACLR, too, several recent randomized clinical trials (RCTs) reported variation in clinical failure rates between 26% and 40% and variation in the graft re-rupture rate of 11% to 22% in a young and active

population[18, 36, 59]. However, in six out of seven of the comparative studies in the SR, it was reported that the failure rates of ACLSR and ACLR were equal[24]. Moreover, since the present SR, two RCTs with two-year follow-up and one RCT with a five-year follow-up comparing ACLSR to ACLR were published. These studies also reported no differences in the outcome of ACLSR compared to ACLR[28, 31, 38]. Thus, in studies with higher levels of evidence, the failure rate of modern ACLSR seems to be comparable to that reported for ACLR.

Nevertheless, the reported failure rate, rate of other complications and reoperation rate for modern ACLSR require improvement. Healing of the sutured ACL is dependent on biomechanical and biological factors[37]. Most clinical studies on modern ACLSR have addressed the biomechanical factors with some sort of augmentation[24]. The biological factors in the hostile intra-articular environment have largely been addressed with the addition of some form of bone marrow access (microfracture or abrasion of the cortex at the femoral ACL attachment site) to stimulate ACL healing, and only a few studies on modern ACLSR have incorporated the addition of a bridging collagen scaffold in their ACLSR technique[24, 38]. However, the addition of a collagen scaffold that bridges the ends of the ruptured ACL seems to improve the healing capacity of the sutured ACL. In fact, extensive animal model studies have reported that this is a prerequisite for an ACL with a midsubstance rupture location to heal properly[37]. In a large RCT on ACLSR with the addition of a collagen scaffold for predominantly non-proximal ACL ruptures, results comparable to those of ACLR were reported[38]. Moreover, a vast reduction of the failure rate and rate of other complications after augmented ACLSR has been reported after addition of a bridging collagen scaffold for ACL ruptures with midsubstance rupture location[13].

Thus, compared to the biomechanical factors that influence the healing of the sutured ACL, biological factors seem to be under-investigated. Therefore, addition of a bio-conductive and -inductive scaffold to the ACL rupture repair site might improve the outcome of modern ACLSR. This scaffold might be tissue-engineered adding cells that improve healing potential to the ruptured ACL tissue, and 3D-engineered to reflect the native shape of the intact ACL. Moreover, since repair instead of reconstruction for ligamentous injuries other than the ruptured ACL has also been proposed, this strategy could be incorporated into the treatment of ligament repair instead of ligament reconstruction in general[19, 42].

Furthermore, concomitant injuries such as meniscal and anterolateral corner injuries have also been described as risk factors for failure and unsatisfactory results after ACL surgery[54]. For this population, treatment of rotatory instability with an anterolateral corner

reconstruction in addition to ACLR with an autologous tendon graft has been reported to reduce failure rate drastically in several prospective and randomized studies[18, 48, 49]. Therefore, addition of an anterolateral corner reconstruction (and treatment of concomitant peripheral knee injuries in general) may reduce the failure rate for young and active patients undergoing DA ACLSR[8, 29].

Thus, the body of high-level and high-quality evidence is still small, and caution must be exercised in assessing the role of modern ACLSR as an effective treatment option for acute ACL ruptures[24]. If ACLSR is to be considered a serious treatment alternative to ACLR, more high-quality research is needed, including RCTs with larger groups of patients that compare ACLSR to ACLR, taking into account the different augmentation and biological healing stimuli techniques and the treatment of injured peripheral structures of the knee.

Role of augmentation in modern anterior cruciate ligament suture repair techniques

Most historical ACLSR techniques did not use augmentation, and residual anterior tibial translational force persisted, which could lead to elongation and failure of the ACLSR[11, 44, 51]. Modern ACLSR may be augmented with a strong, small-diameter braid positioned parallel to the ACL, with only minimal disruption of the ACL attachment sites and ACL tissue, to restrain residual anterior tibial translational force. In the first decade of the 21st century, several biomechanical studies of animal and human cadaveric knees reported that augmentation could restore anterior tibial translation (ATT) to normal values[14-16, 30, 46, 47]. In more recent years, these augmentation techniques have been used in several clinical studies on modern ACLSR[24].

However, there was still a lack of evidence regarding how these modern augmentation techniques affect ATT across the arc of flexion of the knee and after cyclic loading and how the techniques compare against each other and against historical non-augmented ACLSR. These questions were investigated in a biomechanical study of the human cadaveric knee (**Chapter 3**). It was found that, after cyclic loading of the knee, only DA, not SA, was able to maintain restoration of ATT to values similar to the ACL-intact state and reduce ATT compared to the ACL-ruptured state[26]. The same biomechanical study found a dispersion (quantified variation) of the actual position of the tibial and femoral tunnel entrances when compared to their intended isometric points (**Chapter 4**), the extent of which may cause cyclic length changes with knee motion[25]. This might explain the increase of ATT after cyclic

loading of the knee for SA in the setting of a biomechanical study in the human cadaveric knee.

The results of biomechanical studies are, of course, only valid close to time zero. One could argue that the sutured ACL should not be shielded from stress completely in order to heal with proper biomechanical characteristics. In line with this argument, it was reported that DA loses tension within the first six months after surgery, and removal of the DA device did not compromise knee stability[1]. Moreover, SA had already been proposed as a "seatbelt", shielding the repaired ACL against non-physiological forces while it heals, which implies that isometric placement of the augmentation braid would be unnecessary[33]. Indeed, several recent prospective clinical studies with two-year (SA and DA ACLSR) and five-year (DA ACLSR) follow-up have reported no significant or clinically relevant side-to-side differences in anterior-posterior (AP) laxity tests of the knee for ACLSR compared to ACLR with an autologous tendon graft, with "normal" mean ATT values according to the International Knee Documentation Committee (IKDC) Physical Examination Score [22, 28, 31, 38]. From a combined biomechanical and clinical perspective, therefore, both SA and DA help to temporarily maintain the apposition of the suture-repaired ACL tissue while it heals, and both might be viable augmentation strategies for modern ACLSR.

Furthermore, testing protocols in biomechanical studies on ACLSR may not reflect real-life loading conditions. Such studies test with cyclic loading across the full arc of flexion of the knee[16, 43]. In contrast, in the early postoperative rehabilitation phase, the patient focuses on regaining normal gait, which is usually achieved after a few weeks, and during normal gait, most shear forces and strains are transmitted to the ACL in extension and early flexion knee angles only. Moreover, while in a biomechanical study cyclic loading may degrade the ACL stump, under in vivo conditions biological healing may positively affect the AP laxity of the sutured ACL over time, and biomechanical studies cannot take this into account. For these reasons, after ACLSR, the augmentation braid mainly has to shield the suture-repaired ACL in these limited early flexion knee angles. The ultimate goal is for the ACL to heal so that it can withstand these forces and strains on its own in a later phase[12, 35]. Therefore, obtaining and implementing a more accurate profile of the movements of and the forces and torques on the knee joint in the early postoperative rehabilitation phase after surgery (e.g., with modern sensor technology such as ambulant inertial movement units) might improve the applicability of cyclic loading protocols in biomechanical studies on ACLSR to real-life in vivo circumstances.

Nevertheless, biomechanical studies with human cadaveric knees are considered to be appropriate and relevant to investigate modern augmentation devices in ACLSR surgical techniques near time zero. As well as potential ethical issues, however, they have drawbacks including high costs, often older age of the specimens, variability of tissue quality (with tissue degradation after cyclic loading), biohazard and waste[3]. Finite element computer modelling might be used as a substitute to the classic biomechanical study of human cadaveric specimens[3]. One of the proposed advantages is that once a validated simulation model has been developed, it can be reused endlessly at relatively low cost.[3] To be accurate for an individual patient, however, a finite element model for biomechanical analysis and planning of knee surgery might take into account the patient-specific leg and knee alignment and the knee's osseous and soft tissue modulus, as these factors influence the kinematics and kinetics of the knee joint and the leg[4, 54]. These types of finite element knee models (a "digital twin knee") are currently under development for ligamentous and realignment knee surgery and might replace biomechanical studies on the human cadaveric knee altogether[40]. If validated, these "digital twin knees" could be one of multiple parameters in a future patient profile used to reach a true patient-specific treatment pathway, taking into account dynamic biomechanical, subjective (e.g., patient-reported outcome measures), psychological and contextual (e.g., socio-economic, work-related) factors.

Assessment of early and midterm outcomes of modern ACLSR compared to ACLR

Since the first paper on the clinical outcome of modern ACLSR was published in 2014, there has been a surge of publications on this topic[24]. With this evolving body of evidence, more insight has been obtained into patient selection criteria, and certain ACL rupture characteristics, such as rupture location, rupture pattern and disruption of the synovial sheath risk factors, have been reported to influence the outcomes of modern ACLSR[2, 13, 20, 32]. In our RCT, we investigated whether these ACL rupture characteristics could have been identified on the preoperative MRI of the patients who underwent ACLSR (**Chapter 5**)[27]. If so, this information could be used to select which patients could undergo ACLSR instead of ACLR. However, the investigation found only slight to moderate intra- and interobserver reliability for the MRI classification of specific ACL rupture characteristics (ACL rupture location and rupture pattern) and only poor to slight agreement between the MRI classification and arthroscopic findings. Since the MRI in the RCT was performed in the acute phase after knee injury, the classification might be obscured by the absence of clear gap formation and injury-inflicted haemorrhage and oedema, which could cause primary ACL injury signs to overlap predefined ACL rupture location zones[55-57, 60].

Other authors have found higher intra- and interobserver reliability for MRI classification of ACL rupture characteristics[52]. Familiarity with the classification system, use of a different classification system and use of MRI with a higher field strength and a smaller slice thickness with a small gap and oblique sagittal views may improve the reliability coefficients within and between observers[27]. Nevertheless, no other study has compared MRI classification with arthroscopic classification of ACL rupture characteristics directly. To date, therefore, intraoperative classification of ACL rupture characteristics is still the gold standard for selection of the patient's eligibility for ACLSR[27]. An office-based diagnostic needle arthroscopy might improve the identification of ACL rupture characteristics, thus facilitating the selection of patients suitable for ACLSR in the outpatient clinic setting prior to surgery[6, 61].

The evolving body of evidence including animal model studies from the first decade of the 21st century and the results of the early prospective clinical case series, supported further investigation of modern ACLSR as a surgical treatment option for ACL ruptures. When work began for this thesis, the best clinical evidence was for DA ACLSR[9]. However, studies with a high level and quality of evidence were missing. Therefore, an RCT was performed in which the clinical outcomes of DA ACLSR and ACLR were compared[5]. No significant differences were found between ACLSR and ACLR at the two-year (**Chapter 6**) and five-year (**Chapter 7**) follow-up for any of the outcome measures, including several patient-reported outcome measures (PROMs), failure rate, complication rate, reoperation rate and side-to-side difference in the AP laxity of the knee[23, 28]. Although at the two-year follow-up **(Chapter 6**) DA ACLSR was not inferior to ACLR in terms of PROMs as measured with the IKDC Subjective Score (IKDCs), the results at the five-year follow-up (**Chapter 7**) were inconclusive. This course is reminiscent of the results of historical ACLSR that showed deteriorating results over time. No other comparative study of modern ACLSR and ACLR with a five-year (or longer) follow-up is available yet to put this finding into perspective. Nevertheless, in contrast to an RCT that reported inferior outcome of historical ACLSR over ACLR at short-term and long-term follow-up, no significant differences were found between modern DA ACLSR and ACLR for any of the outcome measures[10, 50]. This might suggest that, in contrast to historical ACLSR, modern ACLSR yields equal results to ACLR at midterm follow-up.

In the literature, the number of high-level and quality studies on modern ACLSR is still low. In 2019, our RCT was the only level 1 study with a minimum of two-year follow-up that was included in our SR[24]. More recently, two additional RCTs were published from different author groups comparing modern SA and DA ACLSR with ACLR. First,

Kosters et al. compared DA ACLSR to ACLR with an autologous hamstring tendon graft. No clinically relevant side-to-side difference in AP laxity of the knee was reported, despite being statistically different. Furthermore, no statistically significant differences were found in several PROMs, failure rate, rate of other complication or reoperation rate[31]. Second, Murray et al. compared SA ACLSR with the addition of a collagen scaffold that bridges the gap between the two ends of the ruptured ACL with ACLR with an autologous tendon graft. They reported no inferiority of ACLSR compared to ACLR in terms of PROMs as measured with the IKDCs at two-year follow-up. Furthermore, no significant differences were found for PROMs and AP knee laxity[38]. Thus, in line with the outcomes of our RCT, several other RCTs with different modern ACLSR strategies have also reported no differences in outcome between modern augmented ACLSR and ACLR at two-year follow-up. However, the number of recent RCTs is too low to draw a definitive conclusion on the role of modern ACLSR in the treatment of acute ACL rupture. In our opinion, therefore, there is still a need for more high-quality research, with larger groups of patients, including RCTs focusing on long-term outcomes to evaluate the role of modern ACLSR in the treatment of acute ACL rupture. A multicentre RCT with these characteristics to compare the outcome of SA ACLSR for proximal ACL ruptures with ACLR with an autologous tendon graft has now been initiated and patients are being enrolled[53].

ACLSR is best performed within several weeks after injury to take advantage of the natural healing capacity of the ruptured ACL tissue[34, 39]. It is therefore important that the patients who would benefit from ACL surgery in general and those who would not can be identified. However, it is still under debate how to identify patients who need to undergo ACL surgery or who can be treated non-operatively with a rehabilitation programme alone[7, 17, 45]. Although greater AP stability but equal functional outcome at short-term follow-up has been reported for historical ACLSR compared to conservative treatment, no comparative studies of modern ACLSR and non-operative treatment have so far been published, as reported in our SR [41]. It is therefore important that we improve our insight not only into what a patient would gain from ACLSR compared to ACLR and how the outcomes of ACLSR itself could be improved, but also into which patients would benefit more from ACLSR than from non-operative treatment. This should be investigated in future research on the treatment of acute ACL rupture.

Conclusion

In this thesis, the literature on the clinical outcomes of modern ACLSR techniques was systematically reviewed, the role of modern augmentation techniques in ACLSR was

investigated and the early and midterm outcomes of modern DA ACLSR were assessed in relation to the current surgical gold standard, ACLR. Although overall the level and quality of evidence in this field is low, the work in this thesis and the recent work of others with a high quality and level of evidence show that, contrary to common belief based on historical ACLSR, there may be no difference in the outcome between modern ACLSR and ACLR. Furthermore, this thesis showed that augmentation of the ACLSR with a strong, small-diameter braid positioned parallel to the ACL and shielding the ACL from (some) stress during healing may be one of the important pillars for the success of modern ACLSR.

Modern augmented ACLSR therefore holds promise as an alternative modality to ACLR for the surgical treatment of acute ACL rupture, with possible advantages over ACLR such as recovery of the complex native anatomy and proprioceptive function, the absence of donor site morbidity of the graft and a reduction of the risk of early-onset posttraumatic osteoarthritis. To definitively establish the role of modern ACLSR in the treatment of acute ACL ruptures, however, more high-quality research is needed to compare ACLSR to ACLR and to conservative treatment. Future research should include longer follow-up in larger populations, taking into account the different augmentation and biological healing stimuli techniques and the treatment of injured peripheral structures of the knee.

The quest continues…

Literature

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CHAPTER 9

Summary

Summary

The purpose of this thesis was to investigate the role of modern anterior cruciate ligament (ACL) suture repair (ACLSR) in the treatment of ACL ruptures.

Chapter 1 presents a general introduction to the anatomy and biomechanical function of the ACL, a description of ACL injury, a historical perspective of ACL surgery from ACLSR to ACL reconstruction (ACLR), and the advantages and disadvantages of the current surgical gold standard, ACLR. Furthermore, this chapter sets out the following aims of this thesis: to review the literature on clinical outcomes of modern ACLSR techniques; to investigate the role of augmentation in modern ACLSR techniques and to compare augmented ACLSR to a non-augmented (NA) ACLSR technique commonly used in historical ACLSR studies; and to assess the early and midterm outcomes of modern dynamic augmented (DA) ACLSR in relation to ACLR.

Chapter 2 presents a systematic review of the literature in which recent studies on clinical and patient-reported outcomes of several modern ACLSR techniques are summarized, critically appraised and compared. Modern ACLSR can be augmented with a small-diameter braid positioned parallel to the ACL (augmentation) to negate anterior tibial translational (ATT) forces while the ACL is healing. In static augmentation (SA), this braid is fixed to the femoral and tibial bone directly, and in DA this braid is fixed to the tibial bone indirectly with an additional elastic link (spring-in-screw mechanism). It was found that the overall level and quality of evidence of the 31 reviewed studies was poor, especially for SA ACLSR, and there was a lack of high-quality studies examining long-term outcomes. Moreover, there was high variability in reported failure rates within all ACLSR categories (NA, 0–25%; SA, 0–49%; DA, 0–27%). Revision ACL surgery rate, complication rate and reoperation rate tended to be higher in the DA ACLSR category (0–20%, 2–61% and 2–33%, respectively) than in the NA and SA ACLSR categories (0–8%, 0% and 0–15% for NA; 0–7%, 0–2% and 0–10% for SA), with hardware removal for medical reasons and on patient request contributing substantially to the reoperation rate after DA ACLSR. Furthermore, the results of the systematic review did not support superiority of ACLSR for a proximal rupture location. All these findings made it difficult to interpret differences in clinical and patient-reported outcomes among ACLSR categories and ACL rupture locations. Above all, this review highlighted that, before the current role of ACLSR in the treatment of acute ACL ruptures can be determined, high-quality research is needed with larger groups of patients, including randomized controlled trials (RCTs) comparing ACLSR to ACLR.

Chapter 3 compares the biomechanical properties of two modern augmented ACLSR techniques and one historical NA ACLSR technique in the human cadaveric knee after cyclic loading and across the arc of flexion. Kinematic data were recorded without external loads applied and under 89-N of anterior tibial drawer force. The knee specimens were tested in the following states after 10 and 300 cycles of flexion and extension between 0° and 90°: ACL-intact and ACL-sectioned, NA ACLSR, SA and DA state (SA and DA in randomized order). It was found that only DA resulted in restoration of ATT values similar to those of the ACL-intact state, and lower than the ACL-sectioned state directly post-operation and after cyclic loading, across the arc of flexion of the knee.

Chapter 4 assesses whether, in the biomechanical study presented in Chapter 3, the targeted isometric tunnel placement for the ACL augmentation braid was attained. It was found that there was a dispersion of the actual position of the tibial and femoral tunnel entrances compared to their intended isometric points, the extent of which may cause cyclic length changes with knee motion. By design, DA can compensate for anisometric placement of the augmentation braids' femoral and tibial tunnel position and to some extent absorb the resulting length change across the arc of flexion of the knee. SA cannot, however. An ACLSR with SA will thus be vulnerable to cyclic stretching-out, and this may explain the increase of ATT values after SA and cyclic loading of the knee, as found in the biomechanical study. It was concluded, therefore, that the findings of the studies presented in Chapters 3 and 4 supported further clinical evaluation of DA ACLSR.

Chapter 5 retrospectively investigates whether a preoperative magnetic resonance imaging (MRI) scan could have predicted specific morphological ACL rupture characteristics that were found during arthroscopic ACLSR. Certain ACL rupture characteristics, such as rupture location, rupture pattern and disruption of the synovial sheath, were reported to influence the outcomes of modern ACLSR. To select patients who could undergo ACLSR instead of ACLR based on these ACL rupture characteristics prior to instead of during surgery, it was investigated whether these ACL rupture characteristics could have been identified on the preoperative MRI for the patients who underwent ACLSR. It was found that the agreement between MRI classification and arthroscopic findings of specific ACL rupture characteristics was poor to slight and that the intra- and interobserver reliability for MRI classification of the ACL rupture characteristics was slight to moderate. It was therefore concluded that final assessment of a patient's eligibility for ACLSR based on ACL rupture characteristics should be made at the time of – and not prior to – surgery.

Chapter 6 presents the results at the two-year follow-up of a RCT on patient-reported, clinical and radiological outcomes of DA ACLSR compared with ACLR. With a non-inferiority design, the study included 48 active patients aged 18 to 30 years with an acute ACL rupture. Patients were stratified based on their activity level, after which they were randomized to undergo either DA ACLSR (n = 24) within three weeks after injury or single-bundle ACLR with an autologous semitendinosus tendon graft (n = 24) within two weeks after they met preoperative criteria. It was found that DA ACLSR was not inferior to ACLR in terms of subjective patient-reported outcomes as measured with the International Knee Documentation Committee Subjective Score (IKDCs; the primary outcome measure) two years postoperatively. Furthermore, no statistically significant differences were found between groups for the IKDCs or for any of the secondary – subjective, clinical and radiological – outcome measures. It was therefore concluded that, although no high-level evidence with long-term follow-up existed, DA ACLSR might be considered a viable treatment option for patients with an acute ACL rupture.

Chapter 7 presents the results of the RCT at the five-year follow-up. Since the initial satisfactory short-term results of several historical studies on ACLSR were reported to deteriorate at midterm follow-up, there is a need for RCTs on modern ACLSR with an adequate follow-up period to assess its role in the treatment of ACL ruptures. The results were inconclusive regarding the non-inferiority of DA ACLSR to ACLR in terms of subjective patient-reported outcomes as measured with the IKDCs five years postoperatively. This was due to a wide confidence interval around the median IKDCs of the DA ACLSR group. Nevertheless, no statistically significant difference was found for the IKDCs or for any of the secondary outcome measures between groups. It was therefore concluded that, although DA ACLSR may be a viable treatment option for patients with acute ACL rupture, caution must be exercised when considering this treatment for young, active patients, corresponding to the study's population.

Chapter 8 presents a general discussion of the papers presented in this thesis and how they may assist in determining the role of modern ACLSR in the treatment of acute ACL injury. It also discusses which directions for future research can be recommended.

CHAPTER 10

Samenvatting (Dutch)

Samenvatting (Dutch)

Het doel van dit proefschrift is om de rol van het hechten van de voorste kruisband (VKBH) bij de behandeling van rupturen van de voorste kruisband (VKB) te onderzoeken.

Hoofdstuk 1 geeft een algemene inleiding in de anatomie en biomechanische functie van de VKB, een beschrijving van VKB-letsel, een historisch perspectief op VKB-chirurgie van VKBH tot VKB-reconstructie (VKBR) en de voor- en nadelen van de huidige chirurgische gouden standaard, VKBR. Verder zet dit hoofdstuk de volgende doelstellingen van dit proefschrift uiteen: het beschouwen van de literatuur over klinische uitkomsten van hedendaagse VKBH-technieken; het onderzoeken van de rol van augmentatie in hedendaagse VKBH-technieken en het vergelijken van geaugmenteerde VKBH met een niet-geaugmenteerde (NA) VKBH-techniek die vaak wordt gebruikt in historische wetenschappelijke VKBH-studies; en het beoordelen van de vroege en middellange termijnresultaten van hedendaagse dynamisch geaugmenteerde (DA) VKBH in relatie tot VKBR.

Hoofdstuk 2 presenteert een systematische review van de literatuur. Daarin worden recente studies naar klinische en patiënt-gerapporteerde uitkomsten van verschillende hedendaagse VKBH-technieken samengevat, kritisch beoordeeld en vergeleken. Bij een hedendaagse VKBH kan een stevige draad met een kleine diameter evenwijdig aan de VKB worden geplaatst (augmentatie) om anterieure tibiale translatiekrachten (ATT) teniet te doen terwijl de VKB geneest. Bij statische augmentatie wordt deze draad direct aan het femorale en tibiale bot bevestigd; bij dynamische augmentatie wordt deze draad indirect aan het tibiale bot bevestigd met een extra elastische schakel (veer-in-schroefmechanisme). Er werd vastgesteld dat het algehele niveau en de kwaliteit van de 31 beoordeelde studies slecht was, vooral voor statisch geaugmenteerde (SA) VKBH, en dat er een gebrek was aan studies van hoge kwaliteit die langetermijnresultaten onderzochten. Bovendien was er een hoge variabiliteit in gerapporteerde faalpercentages binnen alle VKBH-categorieën (NA, 0–25%; SA, 0–49%; DA, 0–27%). Het percentage van revisie-VKB-chirurgie, het aantal complicaties en het aantal heroperaties neigde hoger te zijn in de DA-VKBH-categorie (respectievelijk 0–20%, 2–61% en 2–33%) dan in de NA- en SA-VKBH-categorieën (0-8%, 0 % en 0–15% voor NA; 0–7%, 0–2% en 0–10% voor SA). Daarbij droeg het verwijderen van hardware om medische redenen en op verzoek van de patiënt aanzienlijk bij aan het percentage van heroperaties na DA VKBH. Bovendien ondersteunden de resultaten van de systematische review geen superioriteit van VKBH bij een proximale ruptuurlocatie. Al deze bevindingen maakten het moeilijk om verschillen in klinische en patiënt-gerapporteerde

uitkomsten tussen VKB-categorieën en VKB-ruptuurlocaties te interpreteren. De uitkomst van deze review benadrukte vooral dat, voordat de huidige rol van VKBH bij de behandeling van acute VKB-rupturen kan worden bepaald, kwalitatief hoogstaand onderzoek nodig is met grotere groepen patiënten, inclusief gerandomiseerde gecontroleerde onderzoeken (RCT's) waarin VKBH wordt vergeleken met VKBR.

Hoofdstuk 3 vergelijkt de biomechanische eigenschappen van twee hedendaagse geaugmenteerde VKBH-technieken en één historische NA-VKBH-techniek in de menselijke kadaverknie na cyclische belasting en in verschillende flexiehoeken van de knie. Kinematische gegevens werden geregistreerd zonder externe belasting en terwijl er 89-N anterieure tibiale translatiekracht werd aangebracht. De kadaverknieën werden getest in de volgende staten na tien en driehonderd cycli van flexie en extensie tussen nul en negentig graden: VKB-intact, VKB-insufficiënt, na NA VKBH, statische augmentatie en dynamische augmentatie (statische en dynamische augmentatie in gerandomiseerde volgorde). Alleen dynamische augmentatie resulteerde in herstel van ATT-waarden vergelijkbaar met die van de intacte VKB en lager dan die van de insufficiënte VKB direct na de operatie alsmede na cyclische belasting.

Hoofdstuk 4 beoordeelt of, in de biomechanische studie zoals gepresenteerd in Hoofdstuk 3, de beoogde isometrische tunnelplaatsing voor de VKB-augmentatiedraad ook daadwerkelijk werd behaald. Het bleek dat er een spreiding was van de daadwerkelijke positie van de tibiale en femorale tunnelingangen in vergelijking met hun beoogde isometrische punten, van een orde dat dit cyclische lengteveranderingen kan veroorzaken bij flexie en extensie van de knie. Dynamische augmentatie kan vanwege het veermechanisme een anisometrische plaatsing van de femorale en tibiale tunnelpositie van de augmentatiedraad compenseren en tot op zekere hoogte de resulterende lengteverandering tussen de tunnelingangen die optreedt bij flexie en extensie van de knie absorberen. SA kan dat echter niet. Een VKBH met SA zal dus kwetsbaar zijn voor cyclisch uitrekken. Dit kan de toename van ATT-waarden na SA en cyclische belasting van de knie verklaren, zoals werd gevonden in de biomechanische studie. Derhalve werd geconcludeerd dat de bevindingen van de studies zoals gepresenteerd in hoofdstukken 3 en 4 verdere klinische evaluatie van DA VKBH ondersteunden.

Hoofdstuk 5 onderzoekt retrospectief of de preoperatieve MRI-scan de specifieke morfologische VKB-ruptuurkenmerken had kunnen voorspellen die werden gevonden tijdens artroscopische VKBH. Er is beschreven dat sommige kenmerken van een VKB-ruptuur,

zoals de locatie van de ruptuur, het ruptuurpatroon en letsel aan de synoviale bekleding, de uitkomsten van hedendaagse VKBH kunnen beïnvloeden. Om voorafgaand aan – in plaats van tijdens – de operatie de patiënten te selecteren die op basis van deze VKB-ruptuurkenmerken een VKBH in plaats van VKBR kunnen ondergaan, werd onderzocht of deze VKB-ruptuurkenmerken konden worden geïdentificeerd op de preoperatieve MRI van de patiënten die VKBH ondergingen. Er werd gevonden dat de overeenkomst tussen MRI-classificatie en artroscopische bevindingen van specifieke VKB-ruptuurkenmerken slecht tot gering was en dat de intra- en interobserver betrouwbaarheid voor MRI-classificatie van de VKB-ruptuurkenmerken gering tot matig was. Daarom werd geconcludeerd dat de definitieve beoordeling of een patiënt geschikt is om een VKBH te ondergaan op basis van VKB-ruptuurkenmerken moet worden gemaakt tijdens – en niet voorafgaand aan – de operatie.

Hoofdstuk 6 presenteert de resultaten van een RCT over patiënt-gerapporteerde, klinische en radiologische uitkomsten van DA VKBH vergeleken met VKBR bij de follow-up van twee jaar. In de studie met een non-inferioriteit-ontwerp werden 48 actieve patiënten in de leeftijd van 18 tot 30 jaar met een acute VKB-ruptuur geïncludeerd. Patiënten werden gestratificeerd op basis van hun activiteitsniveau. Daarna werden ze gerandomiseerd om een DA VKBH (n = 24) binnen drie weken na het letsel of een VKBR met een autoloog semitendinosus peestransplantaat (n = 24) binnen twee weken nadat ze voldeden aan de preoperatieve criteria te ondergaan. Er werd vastgesteld dat DA VKBH niet inferieur was aan VKBR gemeten met de International Knee Documentation Committee Subjective Score (IKDCs, de primaire uitkomstmaat) twee jaar na de operatie. Verder werden tussen de groepen geen statistisch significante verschillen gevonden voor de IKDCs of voor een van de secundaire – subjectieve, klinische en radiologische – uitkomstmaten. Daarom werd geconcludeerd dat, hoewel er geen bewijs op hooggradig wetenschappelijk niveau met langdurige follow-up bestond, DA VKBH kan worden beschouwd als een reële behandelingsoptie voor patiënten met een acute VKB-ruptuur.

Hoofdstuk 7 presenteert vervolgens de resultaten van de RCT bij de follow-up van vijf jaar. Aangezien eerder beschreven werd dat de initieel bevredigende kortetermijnresultaten van verschillende historische studies over VKBH verslechterden tijdens de follow-up op de middellange termijn, is er behoefte aan RCT's over hedendaagse VKBH-technieken met een adequate follow-up-periode om de rol ervan bij de behandeling van VKB-rupturen te beoordelen. De resultaten waren niet-conclusief met betrekking tot de non-inferioriteit van DA VKBH ten opzichte van VKBR gemeten met de IKDCs vijf jaar na de operatie. Dit was

te wijten aan een breed betrouwbaarheidsinterval rond de mediaan van de IKDCs van de DA-VKBH-groep. Desalniettemin werd tussen de groepen geen statistisch significant verschil gevonden voor de IKDCs of voor een van de secundaire uitkomstmaten. Daarom werd geconcludeerd dat, hoewel DA VKBH een reële behandelingsoptie kan zijn voor patiënten met een acute VKB-ruptuur, voorzichtigheid moet worden betracht bij het overwegen van deze behandeling voor jonge, actieve patiënten, overeenkomend met de onderzoekspopulatie.

Hoofdstuk 8 bespreekt in algemene zin de artikelen die in dit proefschrift zijn gepresenteerd en hoe ze kunnen helpen om de rol van hedendaagse VKBH in de behandeling van acuut VKB-letsel te bepalen. Daarnaast wordt besproken welke richtingen voor toekomstig onderzoek worden aanbevolen.

Appendices with chapter 4

Appendix A: inter- and intraobserver reliability of actual tunnel positions and intended isometric point positions.

	Interobserver reliability	Intraobserver reliability R1	Intraobserver reliability R2
Femoral parameters			
FX t (deep-shallow direction)	0.99	0.99	0.99
FY t (high-low direction)	0.99	0.99	0.99
FX ip (deep-shallow direction)	0.93	0.95	0.95
FY ip (high-low direction)	0.75	0.83	0.80
Tibial parameters			
TX t (medio-lateral direction)	0.99	0.99	0.99
TY t (antero-posterior direction)	0.99	0.99	0.99
TX ip (medio-lateral direction)	0.95	0.91	0.91
TY ip (high-low direction)	0.95	0.94	0.97

R1, rater 1; R2, rater 2; F, femoral; T, tibial; X, x-axis; Y, y-axis; t, tunnel; ip, isometric point.

Appendix B: The size of the femoral grid (mm), four measurements of the positions of the actual femoral tunnels and their intended isometric point positions relative to the grid, and their quantitative and qualitative mean value per specimen.

specimen	FX	FX t 1.1	FX t 1.2	FX t 2.1	FX t 2.2	FX ip 1.1	FX ip 1.2	FX ip 2.1	FX ip 2.2
3	45,1	10,5	10,4	10,5	10,5	9,5	9,7	9,4	9,5
4	47,8	13,7	13,9	13,7	13,7	10,1	10,5	10	10,5
5	38,5	4	4,2	4,1	4	8	7,7	8	8,3
6	48,3	12,3	12,3	12,3	12,1	10,8	10,5	10,8	11,1
7	43,3	9,6	9,8	9,6	9,6	11,1	10,8	11	11,2
8	41,3	10,8	10,6	10,8	10,7	7,8	7,6	7,3	7,5
9	41,1	10,1	10,2	10,1	10,1	8,2	8,2	7,8	8
10	45,8	12,3	12,3	12,3	12,5	9,5	9,9	9,4	9,6
11	44,3	12,4	12,4	12,4	12,4	10,2	10,1	9,5	9,9
12	41,2	8,6	8,4	8,6	8,6	8,8	9,3	9,3	9,4
13	42,6	11,7	11,6	11,7	11,5	10,9	10,7	10,4	10,7
14	44,6	9,2	9,3	9,4	9,2	8,8	9	8,8	9,3
specimen	FY	FY t 1.1	FY t 1.2	FY t 2.1	FY t 2.2	FY ip 1.1	FY ip 1.2	FY ip 2.1	FY ip 2.2
3	24	5	5,1	5,1	5,1	2,2	2,1	2	2,1
4	23,3	0,8	1	0,9	0,8	1,6	1,7	2	1,8
5	20,6	0,5	0,5	0,5	0,6	1,8	1,7	1,8	1,6
6	22,7	0,3	0,2	0,2	0,2	1,4	1,5	1,4	1,6
7	23	2,5	2,5	2,5	2,7	1,1	1,2	1,2	1
8	21,7	1,4	1,6	1,6	1,4	1,3	1,5	1,6	1,4
9	22,8	3	2,9	3	3	1,9	2	1,9	1,7
10	22,2	1,4	1,5	1,4	1,4	1,7	1,7	1,7	1,9
11	23,1	5,1	5,1	4,9	4,9	1,6	1,9	1,8	1,7
12	23,3	6,3	6,3	6,1	6,3	2	1,7	1,9	2,1
13	20,9	2,1	2,2	2,2	2,1	1,6	1,7	1,7	1,6
14	24,3	4,1	4	4,1	4,2	2,2	2	1,8	2

FX, length of the femoral grid along the x-axis; FY, length of the femoral grid along the y-axis; FX t, femoral x-axis tunnel: the distance of the centre of the femoral tunnel (to the y-axis) along the x-axis (in deep-shallow direction); FY t, femoral y-axis tunnel: the distance of the centre of the femoral tunnel (to the x-axis) along the y-axis (in high-low direction); FX ip, femoral x-axis isometric point: the distance of the intended isometric point (to the y-axis) along the x-axis (in deep-shallow direction); FY ip = femoral y-axis isometric point: the distance of the centre of the intended isometric point (to the x-axis) along the y-axis (in high-low direction); 1.1 = measurement 1 of rater 1; 1.2 = measurement 2 of rater 1; 2.1 = measurement 1 of rater 2; 2.2 = measurement 2 of rater 2. Measurement in millimetres unless otherwise indicated.

Appendix C: The size of the tibial grid, four measurements of the positions of the actual tibial tunnels and their intended isometric point positions relative to the grid, and their quantitative and qualitative mean value per specimen.

specimen	TX	TX t 1.1	TX t 1.2	TX t 2.1	TX t 2.2	TX ip 1.1	TX ip 1.2	TX ip 2.1	TX ip 2.2
3	69,6	30,2	30,3	30,4	30,2	35,2	34,9	34,8	34,6
4	78,2	41,4	41,3	41	41,1	42,3	42,4	42,8	42,1
5	68,4	34	34	33,6	33,9	33	33,7	33,6	34,2
6	79,1	37,1	37,3	37,1	37	38,5	38,4	38,2	38
7	72,7	37,2	37,3	37,4	37,5	38,3	37,8	38,3	37,9
8	69,9	32,6	32,7	32,7	32,7	34,2	34,6	34,8	34,1
9	70,4	32,5	32,6	32,1	32,4	35,1	35,9	35	36,1
10	77,2	37,7	37,7	37,7	37,6	38,8	39	39,4	39,7
11	73,5	34,9	34,8	35,2	34,9	36,9	36,8	37,6	37,4
12	68,6	31,4	31,4	31,4	31,4	34,1	33,3	34,1	34,2
13	73,6	35,4	35,3	35,2	35,3	35,8	36,5	36,2	35,8
14	73,3	33,6	33,8	33,6	33,7	36,2	35,9	35,9	35,3
specimen	TY	TY t 1.1	TY t 1.2	TY t 2.2	TY t 2.2	TY ip 1.1	TY ip 1.2	TY ip 2.1	TY ip 2.2
3	46,9	21	20,9	21,1	21	13,1	12,2	12,6	12,6
4	51,7	15	14,8	14,9	14,7	11,8	11,2	12	12,3
5	47,7	19,4	19,4	19,2	19,2	12,3	12,7	12,8	13,2
6	54,1	21,4	21,1	21,2	21,2	16	16	15,9	15,3
7	49,1	18,8	18,7	18,8	18,9	14,9	14,2	14,2	14,1
8	48,2	24,1	24,3	24,2	23,9	14,9	14,1	14,2	14,8
9	47,8	22,7	23	23,1	23	14,5	15,1	15,4	15,3
10	49	20,1	20,1	20,2	20	12,4	12	12,3	12
11	48,2	21,3	21,3	21,5	21,4	12,2	12,9	12,6	12,3
12	46,3	20,8	20,6	20,8	20,8	13,8	13,8	14,2	13,6
13	49,3	19,6	19,7	19,4	19,8	13,3	12,9	13	12,6
14	51,2	17	17,1	17,1	17,1	10,7	10,4	10,9	10,8

TX, the length of the tibial grid along the x-axis; TY, length of the tibial grid along the y-axis; TX t, tibial x-axis tunnel: the distance of the centre of the tunnel (to the y-axis) along the x-axis; TY t, tibial y-axis tunnel: the distance of the centre of the tunnel (to the x-axis) along the y-axis; TX ip, tunnel x-axis isometric point: the distance of the intended isometric point (to the y-axis) along the x-axis; TY ip, tibial y-axis isometric point: the distance of the intended isometric point (to the x-axis) along the y-axis; 1.1 = measurement 1 of rater 1; 1.2 = measurement 2 of rater 1; 2.1 = measurement 1 of rater 2; 2.2 = measurement 2 of rater 2. Measurement in millimetres unless otherwise indicated.

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De leden van de promotiecommissie.

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About The Author

Roy Antonius Gerhardus Hoogeslag was born in Enschede in the Netherlands on the 8th of August, 1977, and grew up in Nijverdal. After graduating from high school at College Noetsele in Nijverdal, he started medical school at the University of Maastricht. During his studies, he developed a special interest in orthopaedic surgery, which resulted in a clinical and research internship. His first scientific publication concerned the relationship between anterior cruciate ligament and anterolateral corner injury of the knee.

Roy graduated from medical school at the end of 2001 and began his professional career in the Orthopaedic Surgery Department of the Isala Clinics in Zwolle (prof.dr. Castelein and dr. Tulp). In 2003, he started his residency in orthopaedic surgery at the University Medical Center (prof.dr. Bulstra) and the Martini Hospital (dr. V. Raaij) in Groningen, during which his special interest in the treatment of disorders of the knee soon became apparent.

In 2009, Roy became a consultant orthopaedic knee surgeon in the Centre for Orthopaedic Surgery and Sport Medicine OCON, Hengelo, the Netherlands, with a focus on the treatment of ligamentous, cartilage and meniscal injuries and correction of knee and leg malalignment. In 2012, he became head of the medical staff of the primary division soccer club FC Twente, Enschede, the Netherlands. Furthermore, in 2013 he helped establish the OCON Sports Medical Centre, in which sports care professionals work in an interdisciplinary setting with the goal of optimizing the prevention, diagnosis and treatment of sports-related injuries and other sports-related complaints.

Over the years, Roy has given several presentations at national and international conferences on these topics, and he has been programme chair of several national and international advanced knee courses. He has also initiated or otherwise been involved in several research projects concerning the improvement of outcomes after treatment of ACL injury and correction of knee and leg malalignment. These projects led to several studies into the repair instead of the reconstruction of the ruptured anterior cruciate ligament, as presented in this thesis.

Roy lives in Nijverdal with his wife Nathalie and their son Ties.