Anatomic anterior cruciate ligament reconstruction: a changing paradigm
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Citation for published version (APA):
SUMMARY AND DISCUSSION
1. Introduction

Anatomy is the basis of orthopaedic surgery. That is why anatomic ACL reconstruction strives to restore as accurately as possible the native ACL anatomy. In anatomic ACL reconstruction, four fundamental principles should be applied: restoring both functional bundles, restoring the insertion sites, matching the graft and tunnel size to the native ACL size and correctly tensioning the graft.\(^1\)\(^2\) The anatomic ACL reconstruction technique has several advantages. Replication of native anatomy leads to better restoration of normal knee kinematics, which is thought to aid in the prevention of early osteoarthritis.\(^3\) Another advantage is that anatomic tunnel placement exposes the graft to normal biomechanical stimuli and in this way creates a more favorable environment for healing and remodeling.\(^4\)

This thesis aims to determine which aspects are important in anatomic ACL reconstruction and to present the results to surgeons in a practically applicable format. This has been accomplished by conducting original research, as well as by systematically reviewing existing medical literature. Knowledge of the anatomy of the knee is crucial for anatomic ACL reconstruction. This involves the anatomy of the ACL, but also that of its surrounding structures. Aspects of ACL surgery that have been studied are the anatomy and size of the intercondylar notch, the lateral intercondylar and bifurcate ridges and factors involved in graft failure after ACL reconstruction. Systematic reviews and a meta-analysis have been used to investigate the theoretical benefits, drawbacks and considerations of double-bundle reconstruction, to evaluate all the different anatomic ACL reconstruction techniques available and to compare the outcomes of single- versus double-bundle ACL reconstruction. Finally, all these findings have been incorporated into a guideline for surgeons, including a flowchart on how to perform anatomic single- and double-bundle ACL reconstruction.

2. Theoretical advantages, drawbacks and considerations of double-bundle ACL reconstruction

Double-bundle reconstruction has become more popular in the past few years. An in-vivo kinematic study has shown that conventional single-bundle ACL reconstruction, which most closely resembles the AM bundle reconstruction, can effectively restore anterior knee stability but does not always successfully return rotational stability.\(^5\) In addition, cadaveric biomechanical studies have proved that double-bundle ACL reconstruction better restores knee kinematics than single-bundle ACL reconstruction.\(^6\) The first research question of this thesis evaluates the theoretical advantages, drawbacks and considerations of double-bundle ACL reconstruction. A review of the relevant literature demonstrates that anatomic, imaging and biomechanical studies have all revealed the complexity of the structure and function of the ACL. The conventional single-bundle reconstruction
techniques only partly restore this complex ligament, whereas the double-bundle ACL reconstruction technique restores both functional bundles so that they can again work together to provide stability of the knee. Therefore, double-bundle reconstruction better replicates the native ACL anatomy, from an anatomic as well as from a functional point of view.

The first randomized controlled clinical trials comparing single- and double-bundle reconstruction, have shown better short-term results after double-bundle reconstruction. However, the long-term results of these and other studies will have to prove whether the advantage of double-bundle reconstruction over single-bundle reconstruction will apply over longer time frames. Besides, double-bundle reconstruction is not without risks. Harner and Poehling emphasized this in their editorial and asked themselves whether the theoretical benefit of double-bundle reconstruction outweighs the increased risk of complications, as the procedure is technically more demanding, has a longer anesthesia time and most surgeons only perform it a couple of times a year. Moreover, there are various techniques for double-bundle ACL reconstruction, with different numbers of tibial and femoral tunnels, different graft choices and different fixation techniques.

The answer to the first research question is that double-bundle reconstruction has anatomic, biomechanical and short-term clinical advantages as compared to single-bundle reconstruction. However, the long-term benefits, especially with regard to reducing the incidence of osteoarthritis, need to be further evaluated.

3. ‘Notch width index’ as a measure of notch size and its correlation with overall notch volume

Not only the number of grafts and tunnels is important in anatomic ACL reconstruction, but also the position of the tunnels. The native ACL stump is mostly used to locate the insertion site. However, in chronic cases, when the stump is usually no longer present, or in revision surgery, the surrounding structures of the ACL play an important role. For a long time the size of the femoral intercondylar notch has been thought to have a relationship with the ACL. It has also been suggested that a small intercondylar notch may lead to an increased risk of ACL rupture. Many different two-dimensional measures of the notch have been used to assess this correlation, such as notch width index and notch area. In the medical literature, conclusions about this relationship vary. This may be due to the two-dimensional nature of the measurements. Therefore, the second research aim of this thesis was to evaluate the frequently used “notch width index” as a measure of notch size, and to determine its correlation with overall three-dimensional notch volume. We hypothesized there are no, or few correlations between the two-dimensional notch width index and the overall three-dimensional notch volume.

A study was conducted to establish whether there is a correlation between the notch volume and the notch width index (NWI) as measured on the three most
frequently used radiographic views: the Holmblad 45°, Holmblad 70° and Rosenberg view. The notch volume of twenty cadaveric knees was measured by means of computer tomography (CT). The Holmblad 45°, Holmblad 70° and Rosenberg notch view radiographs were digitally recreated from the CT-scans for each specimen, and the NWI was measured by two observers.

All three radiographic views proved to be reliable, but showed only a moderate correlation with each other. No correlation was found between notch width index and notch volume. A possible reason for the absence of a significant correlation between NWI and notch volume is that the NWI is an index that corrects a patient’s notch width for the bicondylar width, whereas the overall notch volume is an absolute measurement and is not corrected for the patient’s bone size. The study did find an average NWI in accordance with the findings of previously published papers\textsuperscript{12-14}. Males had larger notch volumes than females, but there was no difference in NWI. A larger absolute notch size in males was also demonstrated in other literature\textsuperscript{12,15-18}. Furthermore, it appeared from this study that there was a moderate correlation between the three radiographic views to measure NWI. This is probably due to the different measurement locations, caused by the different views. The three radiographic methods each result in a different view of the notch and a different part of the notch outlet that is in line with the popliteal groove. In addition, the anatomic variability of the notch, in particular the notch shape, seems to determine the magnitude of the effect of using the different views.

From this study it was concluded that measuring the NWI was very reliable, but that the NWI did not have a positive correlation with overall notch volume\textsuperscript{19}. Therefore, the NWI cannot be used and further studies are needed to determine the relationship between three-dimensional notch volume and ACL injury risk.

4. A classification of the intercondylar notch shape and dimensions in ACL injured patients

The third research aim of this thesis also involved the intercondylar notch and aimed to classify the intercondylar notch shape and dimensions in ACL injured patients. The hypothesis of this study was that it is possible to identify a particular notch shape that is correlated with the smallest notch dimensions and that this notch shape is more prevalent in females.

In a clinical cohort study 102 consecutive patients underwent diagnostic arthroscopic evaluation of the notch. Three categories of notch shape were established: 1. A-shaped; 2. U-shaped; and 3. W-shaped. Two blinded independent orthopaedic surgeons were asked to categorize the recorded notches. Subsequently, the correlations between notch shape, dimensions and demographic factors were calculated.

Of the 102 notches that were evaluated, the majority were either A- or U-shaped. A-shaped notches were narrower in all width dimensions than U-shaped
notches. This is important because narrower shapes can have implications not only for predisposition to ACL injury, but also for the surgical technique of ACL reconstruction. Notches with narrower dimensions may decrease the visibility of the lateral wall, especially when viewed from an anterolateral portal. This, in turn, may lead the surgeon to perform a notchplasty to better visualize the femoral insertion site. Of course, viewing from an anteromedial portal, can obviate the problem of visibility. Notch size and shape may also affect the decision for single- or double-bundle reconstruction. If the notch is very narrow, there may not be enough space for a double bundle graft. Naturally, there are other factors that contribute to the decision for single- or double-bundle, such as a small ACL insertion site, osteoarthritic changes, bone bruising, multiple ligamentous injuries and open physes. Only patient height was found to influence notch shape, with a positive correlation between taller patients and U-shaped and W-shaped notches. Females had a smaller notch width at the base and middle of the notch. Patient height was found to be significantly greater in U- and W-shaped notches than in A-shaped notches. Charlton et al. also evaluated patient height and compared it to notch volume and ACL volume. They concluded that taller patients were more likely to possess greater notch volumes and greater ACL volumes. In addition, Murshed et al. found that, anthropometrically, notch height is greater in men than women. Our study adds to previous conclusions by also suggesting that taller patients are more likely to have a U-shaped notch. Whereas Chaudhari et al. found a positive correlation between patient weight and notch volume, our data did not reveal a significant correlation between notch shape and patient weight or BMI. When notch dimensions were compared between genders, regardless of notch shape, it was found that females had a statistically smaller mean notch width at the base and middle than males. This is consistent with other studies that determined by means of radiographic measurements that females had smaller notch dimensions than males. The femoral notch has been a topic of study for the past two decades. There has been a significant number of studies that suggest that the notch width (absolute width and notch width index) can be correlated to ACL rupture. In these studies the notch was generally evaluated by plain radiographs. The primary drawback of plain radiography is that a precise angle of x-ray is required to optimize notch visualization and that this optimal angle can vary slightly between individuals. By means of direct arthroscopic visualization in our study, we were able to evaluate notch shape and demonstrate a relationship with notch size. However, the limitations of the study were that the measurements were two-dimensional and that no control group, consisting of non-ACL injured subjects, was present.

In conclusion, this study showed that notches with an A-shape were generally the smallest in size. Although females had smaller notch sizes than males, the A-shape was not more prominent in females.
5. The difference in overall notch volume between subjects with and without ACL injury

It has been hypothesized that a smaller femoral notch size may lead to greater forces on the anterior cruciate ligament (ACL), thus increasing the risk of ACL rupture. The fourth research aim was to determine if individuals with ACL injuries have smaller notch volumes than uninjured subjects. A secondary aim was to determine the correlation between intra-operative two-dimensional (2D) notch measurements, patient demographic factors and notch volume.

The 3D notch volume was measured on MRI and compared between fifty patients with ACL injury and fifty patients without ACL injury (controls). Of the fifty patients with ACL injury intra-operative 2D measurements of the notch entrance were taken. The correlations between these 2D measurements, patient demographic factors and 3D notch volume were calculated. In addition, notch size in men and women was compared.

No overall difference was found in notch volume between ACL injured subjects and controls. Only in men there was a statistically significant difference. ACL-injured knees had average notch volumes of 0.9 cm$^3$ (approximately 13%) larger than knees of uninjured male subjects. The clinical relevance of this difference is negligible and it raises doubt about the utility of MRI-based notch volume measurements for predicting ACL injury risk. These findings do not rule out notch size as an influential factor in ACL rupture risk or as a determining factor in surgical management (i.e. single- or double-bundle reconstruction, need for notchplasty). Rather, the results of this study suggest that certain two-dimensional measurements of the notch can be better predictors of ACL rupture risk than notch volume. As discussed above, notch volume and notch entrance size are relatively independent. If contact between the ACL and the notch entrance is a source of ACL damage, then the size of the notch entrance may be a more meaningful predictor of ACL injury than the overall notch volume. However, previous studies of notch entrance size and ACL injury risk produced varying results, perhaps due to a different measurement technique. Intra-operative evaluation and measurements of the notch entrance may be needed to better identify the specific region(s) of the notch most closely related to the ACL.

There were no significant correlations between the 2D dimensions and the 3D notch volume. This suggests that these measurements assess different aspects of the femoral notch geometry; i.e. notch volume is relatively independent of the size of the notch opening. The surprising nature of this observation indicates that the notch geometry is very complex, which may confound attempts to use relatively simple measurements for characterizing notch properties.

Gender, height and weight were positively correlated with notch volume. This is consistent with previous studies which also determined these factors to be
predictive of notch size. However, on the basis of stepwise multiple regression analysis, only patient height was a significant predictor of notch volume, accounting for 42% of the variability in notch volume; adding any of the other variables did not improve the regression. The explanation for this is that the significant demographic factors are interrelated and multi-factorial. The men in our study were on average taller than the women, and the heavier subjects were taller than the lighter subjects. This confounding of gender, height and weight is consistent with existing literature.

This study aimed to determine if individuals with ACL injuries have smaller notch volumes than uninjured subjects. The results indicated that there was no difference in notch volume between patients with ACL injury and patients without ACL injury. Intra-operative notch measurements did not correlate with 3D notch volume. Notch volume was related to patient height, weight and gender, but not to BMI.

6. **The bony ridges may disappear under the influence of Wolff’s law, more often with chronic ACL deficiency than with acute ACL ruptures**

Other anatomic structures important in ACL reconstruction are the bony ridges. The femoral attachment of the ACL has two ridges. The lateral intercondylar ridge (previously called “resident’s ridge”) runs from proximal to distal along the entire ACL femoral insertion. No ACL fibers are found anterior to the lateral intercondylar ridge. Another bony prominence present in the anterior portion of the femoral footprint and running in an anterior to posterior direction is referred to as the lateral bifurcate ridge. During anatomic ACL reconstruction these osseous landmarks are preserved and may serve as guides for tunnel placement. In chronic cases, in which the ACL stump has been resorbed or only fibrous tissue remains, the bony ridges may provide a useful tool in locating the ACL insertion site. However, it has been argued that the ridges may disappear under the influence of Wolff’s law, which explains the development of the ridges by the forces executed by the ACL on the bone. When the ACL is torn and these forces are no longer present, the ridges may therefore gradually disappear. The fifth research aim of this thesis was to determine if there is a difference in the presence of the lateral intercondylar ridge and the lateral bifurcate ridge between patients with sub-acute and with chronic ACL injuries. We hypothesized that the ridges are present less often with chronic ACL deficiency.

Twenty-five patients with a chronic ACL injury were matched for age and gender to twenty-five patients with a sub-acute ACL injury. The lateral intercondylar ridge and the lateral bifurcate ridge were scored as either present, absent, or indeterminate due to insufficient visualization during arthroscopic evaluation by three blinded observers.

The lateral intercondylar ridge was present in 88% of the sub-acute patients
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and in 88% of the chronic patients. The lateral bifurcate ridge was present in 48% of the sub-acute and in 48% of the chronic patients. Therefore, no difference was found in the presence of the femoral bony ridges between patients with acute and with chronic ACL injuries. The conclusion is that often the ridges can still be used to identify the native ACL insertion site after chronic ACL injury, even when the soft tissue remnants have dissolved. The presence of the lateral intercondylar ridge was also found in previous studies. Farrow et al.\textsuperscript{36} could identify the lateral intercondylar ridge in as many as 97% of their specimens. However, these were femurs from a museum collection that had no soft tissue left and were studied in real time without the use of an arthroscope. It was not known if these subjects had ACL injuries.

An explanation for not finding a difference in the presence of the ridges between patients with chronic and with acute ACL injuries, could be that the presence of the ridges is influenced by other factors, for instance age, activity level and surgical delay. These factors were not recorded in the present study. It is possible that more pronounced ridges form as people age, due to the sustained force of the ACL on the femur for a longer period of time. Another factor could be an individual’s activity level. More active people have more force of the ACL, possibly resulting in greater ridge formation in young active people\textsuperscript{37}. The surgical delay may also be a factor affecting the results. The range in surgical delay in the chronic group was 12 to 109 months, but it may take longer after an ACL injury for the bony ridges to disappear. This process may take many years. However, if this is the case, the clinical significance of when not to expect the ridge to be present, would be small since it is rare to perform reconstructive surgery on patients years after their injury. Furthermore, it is plausible that there is actually no difference in the presence of the ridges between patients with acute and with chronic ACL injuries. Surgeons who suggest that the ridges disappear, may be biased by knowing the patient’s history before starting the procedure. When the ACL remnants are no longer visible, it may be more difficult to locate the ridges. Sometimes the ridges cannot be seen, but they can be felt when the wall of the notch is carefully probed\textsuperscript{35}. On the other hand, the observers in our study were specifically looking for both ridges and had no knowledge of patient history.\textsuperscript{38}

This study showed no difference in the presence of the lateral intercondylar and lateral bifurcate ridge between acute and chronic ACL injuries.\textsuperscript{39} This suggests that in both cases these osseous landmarks can be used as a reference in anatomic ACL reconstruction.

7. A systematic review and evaluation of all studies published on anatomic ACL reconstruction

Many techniques for anatomic ACL reconstruction have been proposed. Because of the recent development of the anatomic concept, it still remains unclear
which technique results in the best outcome for the patient. In order to determine this, the different reconstruction techniques need to be evaluated and adequate reporting of the technique in medical literature is necessary. Therefore, our sixth research aim in this thesis was to systematically review and evaluate all studies published on anatomic ACL reconstruction. On the basis of this systematic review we evaluated studies published on anatomic double-bundle ACL reconstruction. The hypothesis was that a substantial percentage of the reviewed surgical technique descriptions do not provide sufficient data for a proper interpretation of the technique and subsequent comparisons of reported outcomes.

First a systematic electronic search was performed in the MEDLINE and EMBASE databases. There were two selection criteria: the studies had to report on a surgical technique for “anatomic double-bundle ACL reconstruction” on skeletally mature living human subjects, and they had to be written in English. A variety of surgical data was collected and analyzed.

Seventy-four studies were included in this review. In the majority of the papers certain surgical factors were adequately reported, including visualizing the native ACL insertion sites, placing the tunnels in the footprint, graft type and fixation method. However, ACL insertion site measurement, femoral intercondylar notch measurement, individualization of surgery and intra-operative/post-operative imaging were poorly reported. Most variety was seen in the knee flexion angle during femoral tunnel drilling and the tensioning pattern of the grafts. Unlike what we had expected, the level of evidence did not influence the quality of reporting in the studies included. Notchplasty is still performed by some authors (12.2% of the included papers) to make the reconstruction easier by visualizing the posterolateral margin of the intercondylar space more clearly. However, the use of an accessory anteromedial portal allows the surgeon excellent visualization of the intercondylar space. The disadvantage of notchplasty lies in the removal of the osseous landmarks of the femoral ACL insertion. This can impede correct anatomic tunnel placement. It can also lead to abnormal graft forces, graft failure and possible re-growth and hypertrophy of the notch in the medium or long-term. None of the studies using notchplasty reported measuring the dimensions of the notch before deciding on performing notchplasty. The knee flexion angle during femoral tunnel drilling was reported only in about 60% of the studies. In anatomic ACL reconstruction the knee flexion angle is very important, as it largely influences the length of the femoral tunnels. Furthermore, the great variation in the reported flexion angle suggests that it is something that is not universally applicable to the wide variety of anatomic ACL reconstruction techniques. Therefore, it should be reported by the author.

Another finding of this systematic review was that there was a discrepancy in the recorded data. 77% and 70% of the papers reported on visualizing the tibial and femoral ACL insertion site, respectively, but as many as 85% and 81% reported placing the tunnels in the center of the tibial and femoral ACL footprint,
respectively. This means that although this review focused on anatomic ACL reconstruction, 15% of the studies did not report placing the tibial tunnels in the center of the native ACL insertion site and 19% did not report placing the femoral tunnels in the center of the native ACL insertion site. This illustrates the need for a proper definition and reporting of “anatomic ACL reconstruction”.

Overall, it was found that a variety of surgical data is greatly underreported in current literature on anatomic double-bundle ACL reconstruction. Of course, not reported does not necessarily mean not performed. However, as the level of medical research is very high today, authors should be held up to a certain standard. For a good interpretation of the results of a published study, it is important to know the surgical details of the procedure that was followed. Anatomic ACL reconstruction can be and is performed in many ways. It is a relatively new and technically demanding surgical procedure. We do not know yet what is the best way to perform it. Therefore, studies that report on an anatomic ACL reconstruction technique should provide adequate and detailed information that allows for fair and detailed comparison and interpretation of the outcomes. A limited description of the technique does not necessarily make a paper less valid, but it causes restrictions to the interpretation of the outcomes and to the possibility of pooling the outcomes with similar studies. This is especially important with a view to comparing double-bundle to single-bundle ACL reconstruction. Both procedures should be performed in an anatomic fashion to show the potential benefit of one over the other.

It was concluded that for most surgical data, there was a gross underreporting of specific operative technique data. The details of an “anatomic” operative technique are crucial for valid interpretations of the outcomes. Therefore, journals should encourage authors to report their surgical technique in a specific and standardized way and journal editors should instruct their reviewers on what aspects of the surgical technique they should evaluate for adequate reporting.

8. The causes and determining factors of ACL reconstruction failures

The anatomic ACL reconstruction principle can also be applied to revision surgery.45 The increasing number of ACL reconstructions will lead to more failures and consequently more revision surgeries. It is important to determine the cause of failure, so that it may be avoided in primary and revision procedures. Therefore, the seventh research aim of this thesis was to determine the most common graft rupture patterns of previously reconstructed double-bundle ACL reconstruction cases, seen at the time of revision surgery. Subsequently, the pattern of injury was compared to that of the native ACL. The influence of certain factors such as age, gender, time between the initial ACL reconstruction and re-injury, tunnel angle and etiology or mechanism of failure on the injury pattern were determined. The hypothesis was that there is a correlation between the factors mentioned above and
the graft rupture pattern.

Forty patients who presented for revision surgery after previous double-bundle ACL reconstruction, were enrolled. Three orthopaedic surgeons independently reviewed the arthroscopic videos and determined the rupture pattern of both the anteromedial and posterolateral grafts. The graft rupture pattern was then correlated to the factors mentioned previously.

The most common rupture pattern in ACL revision cases after previous double-bundle reconstruction was mid-substance rupture of the AM bundle with either mid-substance rupture, proximal rupture, or elongation of the PL bundle, as well as an isolated proximal AM bundle rupture with an intact PL graft. These four patterns characterized approximately 65% of all ruptures. This differs from the most frequent rupture pattern seen in the native ACL, as reported by Zantop et al. Their study demonstrated proximal rupture of the AM bundle with either proximal or mid-substance rupture of the PL bundle as the most common patterns of injury. However, despite this difference, we did see similar results for the occurrence of ruptures of both bundles at the same level, and for the relative incidence of an intact PL bundle. In another series of ACL revision surgeries, Kaz et al. also reported an isolated AM bundle rupture with an intact PL bundle among three double-bundle re-ruptures.

Patient-related factors such as age and gender showed no correlation with the pattern of rupture. But the time interval between the initial ACL reconstruction and the re-injury significantly influenced the rupture pattern. A longer period of time was associated with more proximal ruptures of the graft, whereas a shorter interval resulted in more distal and mid-substance ruptures. This finding may be the result of different degrees of healing or “ligamentization” of the reconstructed ACL graft. In other words, when the graft has been given more time to heal and remodel, the resultant re-injury pattern is most similar to the native ACL, i.e. proximal rupture of the graft.

The graft tunnel angle also had a significant effect on the rupture pattern. However, post-hoc analysis was unable to specify this. We believe that tunnel positioning is a key determinant of the biomechanical function of the knee. Theoretically, variable graft tunnel positioning should result in differences in forces seen by the graft. So we expected differences in rupture patterns as the tunnel position is changed. Further research is needed to investigate and validate these principles.

Finally, this study showed a relationship between the rupture pattern and the etiology of failure. When the patient reported the actual traumatic event, the graft was more often ruptured. On the other hand, the atraumatic failure group more frequently demonstrated elongation of the graft. We suppose that this is a result of the tunnel placement during the initial procedure. If the tunnel is placed outside the native ACL insertion site, this can cause a malfunctioning graft that is exposed to unusual forces and as a result will elongate in time.
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We concluded that the most common pattern of graft re-rupture was mid-substance AM and mid-substance PL. As the space of time from the initial double-bundle ACL reconstruction till revision surgery increased, the pattern of injury more closely resembled that of the native ACL.

9. A meta-analysis of all (quasi-)randomized and observational studies comparing single- and double-bundle ACL reconstruction

Currently, both single- and double-bundle ACL reconstruction are performed and there is a need to compare the results. Recent prospective, randomized, quasi-randomized and observational level I and level II studies have reported favorable clinical outcomes after double-bundle ACL reconstructions\(^7\)\(^9\). This thesis includes a meta-analysis of all (quasi-)randomized and observational studies comparing single- and double-bundle ACL reconstruction. The first hypothesis was that anatomic double-bundle ACL reconstruction leads to a better restoration of anterior and rotational laxity and range of motion than single-bundle reconstruction. The second hypothesis was that there is no difference between non-anatomic single- and double-bundle ACL reconstruction.

A search was carried out in the MEDLINE, EMBASE, CINAHL and Cochrane databases. All randomized, quasi-randomized, and observational clinical trials that reported the outcome of double- versus single-bundle ACL reconstruction were included. The primary outcomes of this meta-analysis were anterior laxity (KT-arthrometer), pivot shift and range of motion; secondary outcomes were Lachman test, peak knee extension torque, return to activity, validated patient-reported outcome instruments, failure rate, complication rate, patient satisfaction and health care costs. The quality of the studies that were included was scored by means of the GRADE Checklist. Anatomic and non-anatomic reconstructions were analyzed separately.

A total of twelve studies (1127 subjects) was included in the analysis, five of which were randomized. For the anatomic single- and double-bundle ACL reconstruction there was a statistically significant difference in favour of anatomic double-bundle reconstruction for anterior laxity as measured by the KT-arthrometer and for the pivot shift test. There was a 0.7 mm decrease in anterior laxity after anatomic double-bundle reconstruction as compared to anatomic single-bundle reconstruction for the randomized studies. This was confirmed by the observational studies, which showed a decrease of 1.3 mm anterior laxity after anatomic double-bundle reconstruction. Additionally, better anterior-posterior stability was demonstrated by a decreased risk of a positive Lachman test after anatomic double-bundle reconstruction as compared to anatomic single-bundle reconstruction. For the pivot shift test, there was a risk reduction of 71% of a positive pivot shift after anatomic double-bundle reconstruction compared to single-bundle reconstruction for the randomized trials. A similar finding was
obtained from the observational studies. The increased rotational stability can be explained by the addition of a PL bundle to control rotation of the knee, as previously shown in cadaveric studies. The pivot shift test is an important outcome for the comparison between single- and double-bundle ACL reconstruction and it is the only available clinical examination to detect rotational instability. It also correlates with the patient-reported outcome and possibly with the future development of knee osteoarthritis. Range of motion, IKDC Knee Ligament Rating, Lysholm score and complication rate did not differ between anatomic single- and double-bundle reconstructions. No major complications were identified for either anatomic single- or double-bundle reconstructions in any of the studies that had been included in the meta-analysis. Isokinetic peak torque, return to activity, IKDC Subjective Knee Form score, Cincinnati Knee Score, KOOS, Tegner Activity score, failure rate, patient satisfaction and health care costs could not be pooled. This was either because these outcomes were only measured in one of the included studies, or because there was variability in the way the outcomes were reported amongst the studies included in the meta-analysis.

Non-anatomic reconstruction techniques were analyzed separately. There were no statistically significant differences in any of the primary or secondary outcomes between non-anatomic single- and double-bundle reconstruction, with the exception of range of motion. On the basis of the results of one randomized study and two observational studies the conclusion was that the risk of an extension deficit is higher for non-anatomic double-bundle reconstruction than for non-anatomic single-bundle reconstruction. Theoretically, it is possible that non-anatomic double-bundle ACL reconstruction induces an extension deficit more often than non-anatomic single-bundle reconstruction. If the tunnels are placed outside the native ACL insertion site and the graft size is not determined by the insertion site size, the notch could be overfilled. During double-bundle reconstruction there is also a greater chance of overstraining the knee by applying too much tension to both grafts and of using improper knee flexion angles during graft fixation.

Analysis of the quality of the included studies revealed that the majority had at least one major limitation in the research protocol that could have negatively affected the quality of the results.

The present meta-analysis included twelve studies, which is 25% more than the previous meta-analysis on this topic, in which Meredick et al. included nine studies. Moreover, in the present study the analysis was performed with two subgroups defined a priori: anatomic reconstruction and non-anatomic reconstruction. Another difference with the previous meta-analysis was the set of criteria by which the data were analyzed. The previous meta-analysis compared “normal” and “nearly normal” results to “abnormal” and “severely abnormal” results.

In the present study we compared “normal” to everything else. This decision
was based on our philosophy that the difference between single- and double-bundle reconstruction can be judged from the percentage of “normal” results. If double-bundle reconstruction consistently yields more “normal” outcomes, this may indicate that normal knee kinematics are better restored, which is beneficial to high-demand athletes and may prevent osteoarthritis in the long term.

Though the meta-analysis showed a difference between single- and double-bundle ACL reconstruction for findings from the physical examination, we were unable to detect differences for patient-reported outcomes. The obvious reason that the benefit of one treatment over the other in terms of patient-reported outcomes could not be shown, is that almost all of the patient-reported outcomes were underreported. The included studies differed in the patient-reported measures that were used. This wide variety of patient-reported outcome measures led to heterogeneous results that could not be pooled. This made the meta-analysis inconclusive. In the future, sufficiently powered randomized trials comparing anatomic single- and double-bundle reconstruction focusing on patient-reported outcomes will be needed. Furthermore, we recommend the universal adoption of the IKDC Subjective Knee Form for reporting patient-reported outcomes in all studies comparing single-bundle and double-bundle ACL reconstruction. This recommendation is based on extensive psychometric testing, availability of normative data and translation of the IKDC Subjective Knee Form into many languages. Besides, longer follow-up may be needed to detect differences in patient-reported outcomes arising in the course of time due to the development of post-traumatic knee osteoarthritis.

The research aim of the present study was based on a meta-analysis comparing single-bundle and double-bundle ACL reconstruction for both anatomic and non-anatomic reconstructions, which included 12 studies and 1127 subjects. Compared to anatomic single-bundle reconstruction, anatomic double-bundle reconstruction demonstrated better anterior laxity, as measured by the KT arthrometer and Lachman test, and better rotational stability, as measured by the pivot shift test. There was no evidence of a benefit of non-anatomic double-bundle over non-anatomic single-bundle reconstruction for any of the assessed outcomes. Non-anatomic double-bundle reconstruction had a higher risk of extension deficit than non-anatomic single-bundle reconstruction. However, the majority of the included studies had at least one major limitation in research plan that affected the quality of the study.

10. A guideline for performing anatomic single- and double-bundle ACL reconstruction

The ultimate aim of this thesis was to combine the findings of existing research with newly acquired results in order to improve the outcome of ACL reconstructive surgery and raise the quality of patient care. This was accomplished by developing
a guideline for performing anatomic single- and double-bundle ACL reconstruction, based on the studies in this thesis and previously published studies. We chose to do this in the format of a flowchart intended to aid surgeons in performing anatomic ACL reconstruction. We supplemented this flowchart with a guideline that contains more detailed information on anatomic ACL reconstruction and its pitfalls and also with helpful figures and references to relevant literature.

Such a flowchart has several advantages. It is a dynamic document that can easily be updated when new information becomes available about the anatomy of the ACL and about how better to reproduce it. The guideline includes a discussion of the most common pitfalls to be avoided in ACL surgery. For instance, non-anatomic tibial and femoral tunnel placement represents one of the most important causes of ACL graft failure. If the tibial tunnels are placed too anteriorly, this may lead to roof impingement, which is associated with loss of extension and abrasion of the graft. To prevent this, some surgeons move the tibial tunnel more posteriorly. However, this approach creates tunnel mismatch. A tibial tunnel positioned at the PL insertion site is often combined with an AM or a high AM femoral tunnel. Tunnel mismatch is common if the femoral AM tunnel is drilled in a transtibial fashion. It results in tunnel placement outside of the native insertion site, which may cause abnormal knee kinematics. Various studies have demonstrated that non-anatomic tunnel placement creates limited range of motion, higher than physiologic graft tension and ultimately graft failure. Biological healing of the graft-bone interface may also be affected. Recent studies have already shown the benefits of adding a PL bundle, but we also prefer double-bundle reconstruction because the normal anatomy of the ACL should be restored. However, by the same anatomic reconstruction principle single-bundle reconstruction can also be performed in anatomic fashion when indications for this are present. Most of the published clinical studies comparing single-bundle to double-bundle reconstruction do not present a fair comparison, since in many cases one or both surgical procedures were not performed anatomically. For example, a transtibial single-bundle and an anatomic double-bundle were compared. In addition, associated injuries such as cartilage defects and meniscus tears should be considered as exclusion criteria. The research should focus on isolated ACL injuries. Randomizing patients for a trial comparing anatomic single-bundle to anatomic double-bundle reconstruction is difficult because the patient’s individual anatomy should determine the type of procedure. Furthermore, the lack of readily available, reliable and valid clinical outcome measures makes it difficult to compare different anterior cruciate ligament reconstruction techniques. Various authors use different outcome measures, and in an office setting it is difficult to quantify differences in rotational stability in absolute terms. The use of more accurate and standardized outcome measures will demonstrate the benefits of anatomic anterior cruciate ligament reconstruction with regard to the restoration of the normal structure and function of the knee. For example, currently important
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outcome measures, such as range of motion, are underreported\textsuperscript{63}, even though it gives important clues to the accuracy of tunnel placement and the presence of impingement.

The flowchart resulting from this thesis incorporates the fundamental principles that should be taken into account when performing anatomic ACL reconstruction: respecting the anatomy, replicating the native ACL insertion site to restore normal knee kinematics and individualizing ACL surgery for each patient. Anatomic ACL reconstruction intends to replicate normal anatomy and restore normal kinematics to advance long-term knee health. The flowchart serves as a guideline for a systematic approach to each case: first the normal anatomy and injury pattern are identified, then the ACL reconstruction is tailored to closely replicate the native anatomy of the patient. The flowchart is applicable to both single- and double-bundle reconstruction and even to revision and augmentation surgery.

Although there is still much to be learned about anatomic ACL reconstruction methods, we believe that our flowchart is already a useful instrument for surgeons to perform successfully anatomic single- and double-bundle ACL reconstructions.

References

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