

The Impact of Osseous Malalignment and Realignment Procedures in Knee Ligament Surgery

A Systematic Review of the Clinical Evidence

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Background: Failure rates of knee ligament surgery may be high, and the impact of osseous alignment on surgical outcome remains controversial. Basic science studies have demonstrated that osseous malalignment can negatively affect ligament strain and that realignment procedures may improve knee joint stability.

Hypothesis/Purpose: The purpose of this review was to summarize the clinical evidence concerning the impact of osseous malalignment and realignment procedures in knee ligament surgery. The hypotheses were that lower extremity malalignment would be an important contributor to knee ligament surgery failure and that realignment surgery would contribute to increased knee stability and improved outcome in select cases.

Study Design: Systematic review; Level of evidence, 4.

Methods: According to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, a systematic electronic search of the PubMed database was performed in November 2015 to identify clinical studies investigating (A) the influence of osseous alignment on postoperative stability and/or failure rates after knee ligament surgery and (B) the impact of osseous realignment procedures in unstable knees with or without additional knee ligament surgery on postoperative knee function and stability. Methodological quality of the studies was assessed using the Oxford Centre for Evidence-Based Medicine Levels of Evidence and the Coleman Methodological Score (CMS).

Results: Of the 1466 potentially relevant articles, 28 studies fulfilled the inclusion and exclusion criteria. Average study quality was poor (CMS, 40). For part A, studies showed increased rerupture rate after anterior cruciate ligament (ACL) replacement in patients with increased tibial slope. Concerning the posterior cruciate ligament (PCL)/posterolateral corner (PLC)/lateral collateral ligament (LCL), varus malalignment was considered a significant risk factor for failure. For part B, studies showed decreased anterior tibial translation after slope-decreasing high tibial osteotomy in ACL-deficient knees. Correcting varus malalignment in PCL/PLC/LCL instability also showed increased stability and better outcomes.

Conclusion: In cases of complex knee instability, the 3-dimensional osseous alignment of the knee should be considered (eg, mechanical weightbearing line and tibial slope). In cases of failed ACL reconstruction, the tibial slope should be considered, and slope-reducing osteotomies are often helpful in the patient revised multiple times. In cases of chronic PCL and/or PLC instability, osseous correction of the varus alignment may reduce the failure rate and is often the first step in treatment. Changes in the mechanical axis should be considered in all cases of instability accompanied by early unicompartmental osteoarthritis.

Keywords: knee instability; osseous geometry; tibial slope; ACL revision; high tibial osteotomy

Primary anterior cruciate ligament reconstruction (ACLR) generally leads to a good outcome and has a revision rate of between 1.6% and 2.1%, as reported in the Swedish National Knee Ligament Registry.⁷ With follow-up longer

than 10 years, the ACL graft rupture rate increases to 6% (range, 0%-3%) and clinical failure occurs in approximately 10% of ACLR cases (range, 2%-26%).¹¹ Revision of a previously reconstructed ACL shows even higher rerupture rates of approximately 13.7%.⁵⁹ Furthermore, outcomes with subsequent revisions are dismal, with only 4 of 15 (27%) patients returning to their prior levels of activity.²⁰ Additionally, based on long-term follow-up, osteoarthritis

The Orthopaedic Journal of Sports Medicine, 5(3), 2325967117697287
DOI: 10.1177/2325967117697287
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develops in 21% to 48% of patients after combined ACL, meniscus, and cartilage injuries but in only 0% to 13% of patients with isolated ACL rupture.⁴⁶

Combined surgical interventions of ACLR and high tibial osteotomy (HTO) are performed in cases of medial compartment osteoarthritis and ACL insufficiency.³⁴ In a systematic review that included 11 studies, simultaneous HTO and ACLR showed good restoration of anterior stability, alleviation of medial compartment osteoarthritis, improvement in subjective evaluations, and a predictable return to recreational sports.³⁴ In addition to alteration of the weightbearing line with HTO, the 3-dimensional osseous geometry has an important impact on knee stability—an observation that has been verified in several basic science studies but has been studied less frequently in clinical settings.^{1,3,17,18,29,47,50,54}

In a landmark biomechanical cadaveric study, Agneskirchner et al¹ demonstrated the role of the tibial slope in anteroposterior knee stability, which is most important in cases of ACL or posterior cruciate ligament (PCL) rupture.^{18,47,50,54} Giffin et al¹⁹ investigated the effect of increasing the anterior-posterior slope on knee kinematics and in situ forces of the cruciate ligaments in 10 cadaveric knees. The authors found that an increased tibial slope led to a relative anterior shift in the resting position of the knee, which was most prominent during knee extension and diminished during knee flexion. In addition, the knee was translated anteriorly throughout the range of motion. The authors concluded that increasing the tibial slope may be beneficial in reducing tibial sag and increasing stability in a PCL-deficient knee. In a computer model study, Shelburne et al⁵¹ found that changes in the tibial slope affect tibial shear forces, anterior tibial translation, and knee ligament loading during activities of daily living, such as standing, squatting, and walking. Furthermore, coronal plane alignment (varus/valgus) is important for collateral ligament stability, especially in cases of posterolateral corner (PLC) instability.²⁹ van de Pol et al⁵³ showed that pronounced varus alignment with lateral joint opening (varus thrust) can also lead to increased forces on the ACL. Furthermore, medial collateral ligament tension is influenced by the coronal alignment.^{2,21} However, there are also contradictory findings, and overall, the relevance of these basic science results to clinical outcome is very vague at present.¹⁷

The primary aim of this systematic review was to summarize current clinical knowledge about the influence of

3-dimensional osseous knee alignment on knee ligament surgery outcomes. The secondary aim was to investigate the role of realignment surgery on knee stability with or without knee ligament reconstruction. The hypothesis was that 3-dimensional knee alignment would be an important contributor to recurrent instability and graft failure after knee ligament surgery and that realignment surgery would contribute to increased knee stability and improved outcome in selected cases.

METHODS

This systematic review was performed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.³⁹ A systematic electronic search of the PubMed database was performed in November 2015 to identify clinical studies investigating (A) the influence of osseous alignment on postoperative stability and/or failure rates after knee ligament surgery and (B) the impact of osseous realignment procedures in unstable knees with or without additional knee ligament surgery on postoperative knee function and stability. The following search terms were used in the title and abstract fields: (((Knee) AND (Anterior cruciate ligament OR ACL OR posterior cruciate ligament OR PCL OR posterolateral corner OR PLC OR lateral collateral ligament OR LCL OR fibular collateral ligament OR FCL OR posteromedial corner OR PMC OR medial collateral ligament OR MCL OR multiligament OR stability OR instability)) AND (Varus OR valgus OR alignment OR malalignment OR slope OR thrust OR hyperextension OR osteotomy)) NOT (Arthroplasty OR knee replacement). No limits were placed on the date of publication. In addition to the electronic search, the reference lists of all included articles and review articles identified from the electronic search were manually searched for additional relevant articles.

For the purpose of this systematic review, only clinical studies that specifically investigated the following were included: the influence of lower-limb alignment on postoperative stability and/or failure after knee ligament surgery, the influence of realignment osteotomy with or without additional knee ligament surgery on knee stability, and the results of revision ligament reconstruction with additional realignment surgery in patients in whom malalignment was considered the primary reason for failure of the reconstruction procedure. Additional inclusion criteria were as

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One or more of the authors has declared the following potential conflict of interest or source of funding: T.T. is a consultant for Arthrex and Bauerfeind. J.P. is a consultant for Stryker. S.H. is a consultant for Arthrex. M.T.H. is a consultant for Depuy Synthes and Smith & Nephew; received a research grant from Mathys; and is a paid speaker for Arthrex and Zimmer. A.B.I. is a consultant for Arthrex and receives royalties from Arthrex and Arthrosurface.

follows: English- or German-language studies, studies published online or in print in a peer-reviewed journal, studies reporting the results of 5 or more patients, studies on patients of any age, and clinical trials of all levels of evidence. The exclusion criteria were as follows: meeting abstracts and proceedings, in vitro or animal studies, clinical studies with insufficient outcome data, and any other type of article, such as technical notes, case reports, or narrative or systematic reviews.

Two reviewers (T.T., M.J.F.) independently screened the titles and abstracts of all articles for relevance according to the inclusion and exclusion criteria. If no abstract was available, the full-text article was obtained to assess the relevance of the study. The full text of all articles that were not excluded during the initial screening process was obtained and reviewed by the same 2 reviewers for possible inclusion in the systematic review. Any disagreement on article eligibility was resolved through discussion until a consensus was reached. For each study that met the inclusion criteria, the author names, year of publication, purpose, study design, follow-up protocol, main results, and level of evidence according to the Oxford Centre for Evidence-Based Medicine were recorded.⁵⁸ Data were extracted by 1 reviewer (M.J.F.) and verified by a second reviewer (T.T.). Any disagreement was resolved via consensus among the reviewers.

Quality Assessment

Two reviewers (T.T., M.J.F.) independently evaluated all included studies and assigned a level of evidence (level 1-4).³⁸ The methodological quality of each study was evaluated using the Coleman Methodology Score (CMS).¹⁰ The CMS is calculated from a 2-part, 10-item questionnaire, scored from 0 to 100 (excellent, 85-100; good, 70-84; fair, 55-69; poor, <55), that has been used in the evaluation of both randomized controlled trials and nonrandomized controlled trials.

RESULTS

Literature Search

Through the electronic and manual search of the relevant reference lists, a total of 1466 potentially relevant articles were identified. After screening the title and abstract of the articles followed by analysis of the full text, a total of 28 studies fulfilled the inclusion and exclusion criteria and were included in this systematic review. The search results are summarized in Figure 1.

No clinical studies investigating the influence of osseous alignment or realignment surgery in cases of medial instability or repair/reconstruction of the medial ligamentous structures were identified.

Quality Assessment

The average CMS of the included studies was 40.1. The primary limitation was the study design in most studies

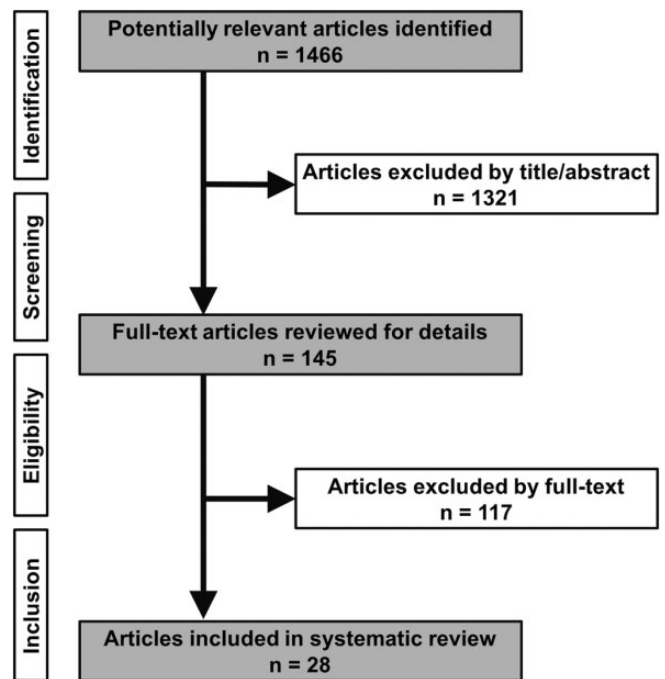


Figure 1. Flowchart of the search strategy in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.

(0.4/15). No prospective controlled or randomized study was performed. Other limitations included the lack of description of postoperative rehabilitation and assessment of patient compliance with rehabilitation (0.2/10) as well as outcome assessment (2.5/15). Strengths of these studies included a mean follow-up duration of longer than 24 months (4/5) in most studies, the use of appropriate outcome measures (8.1/10), and diagnostic certainty (4.3/5).

Part A: Clinical Studies Investigating the Influence of Osseous Alignment on Postoperative Stability and Failure Rates After Knee Ligament Surgery

Anterior Cruciate Ligament. A total of 10 studies were identified (Table 1). One study had level 2 evidence, 6 studies had level 3 evidence, and 3 studies had level 4 evidence. In a prospective multicenter study of patients undergoing revision ACLR, malalignment was rated as the cause of failure in 4% of patients. However, the authors did not provide details about the type of malalignment.³⁷ With regard to coronal malalignment (varus/valgus), the results of the included studies are inconclusive. Won et al⁵⁷ observed that patients undergoing revision ACLR were significantly more likely to have varus malalignment $>5^\circ$ than patients undergoing primary ACLR. Noyes and Barber-Westin⁴² found that varus alignment was a factor contributing to failure of ACLR procedures in 25% of patients. On the other hand, Kim et al²⁸ compared the results of patients with different amounts of primary varus malalignment undergoing ACLR and did not observe any differences in functional outcome. However, it must be noted that patients with a varus thrust

TABLE 1
Clinical Studies Investigating the Influence of Osseous Alignment on Postoperative Stability and Failure Rates After ACLR^a

Author(s), Year	Purpose	Study Design	Follow-up	Main Results	Level of Evidence
The MARS Group et al, 2010 ³⁷	To provide a descriptive analysis of demographic and clinical features of patients undergoing revision ACLR	<ul style="list-style-type: none"> • Prospective multicenter study of patients undergoing revision ACLR • A total of 460 patients were enrolled • As part of the study, the mode of failure of the previous ACLR was reported by the surgeon 	—	<ul style="list-style-type: none"> • Mode of failure was traumatic in 32% of cases, technical in 24%, biologic in 7%, a combination of factors in 37%, and infection in <1% • Malalignment was regarded as a cause of failure in 4% of cases 	2
Kim et al, 2011 ²⁸	To evaluate whether stability and function differ in patients after ACLR with differing degrees of preoperative primary varus malalignment	<ul style="list-style-type: none"> • Retrospective evaluation of 201 patients after sb ACLR • Varus alignment was analyzed preoperatively on standing hip-knee-ankle radiographs, and MAD was measured • Patients with varus thrust and/or grade >II OA in the medial compartment were excluded • Patients were categorized into 4 groups according to their MAD: 0-4 mm (n = 67), 5-9 mm (n = 53), 10-14 mm (n = 38), and >15 mm (n = 43) 	45 mo	<ul style="list-style-type: none"> • No statistically significant differences in anterior or rotational stability or in functional scores were observed between the 4 groups 	4
Won et al, 2013 ⁵⁷	To investigate whether patients undergoing revision ACLR have varus malalignment more frequently than patients undergoing primary ACLR	<ul style="list-style-type: none"> • Retrospective comparison of 58 patients undergoing revision ACLR with 116 age- and sex-matched patients after primary ACLR • The mechanical tibiofemoral angle and the weight-loading line of the knee were measured preoperatively on standing whole-limb radiographs 	—	<ul style="list-style-type: none"> • Patients undergoing revision ACLR had varus malalignment in terms of a tibiofemoral angle >5° or a weight-loading line <25% more frequently than patients undergoing primary ACLR (19% vs 8% and 22% vs 9%, respectively) 	3
Noyes and Barber-Westin, 2006 ⁴²	To determine factors that may have caused failure of 32 ACLR procedures in 21 patients undergoing revision ACLR (secondary purpose)	<ul style="list-style-type: none"> • Prospective study of 21 patients undergoing revision ACLR • A review of medical records, operative notes, radiographs, and MRI scans was conducted to determine factors that contributed to failure of primary ACLR 	—	<ul style="list-style-type: none"> • Varus osseous alignment was a factor contributing to failure of ACLR in 8 procedures (25%) • Varus alignment was the only identified causal factor in 2 procedures (6%) and one of multiple causal factors in 6 procedures (19%) • 7 knees (33%) required HTO to correct varus malalignment before or during revision ACLR 	4
Saito et al, 2015 ⁴⁹	To compare postoperative outcomes after anatomic db ACLR between cases of extreme knee hyperextension and cases of normal to mild hyperextension	<ul style="list-style-type: none"> • Retrospective evaluation of 100 patients after db ACLR • Sagittal alignment was evaluated on lateral radiographs by measuring the extension angle, defined as the angle between the anterior cortex of the femur and the posterior cortex of the tibia 	28 mo	<ul style="list-style-type: none"> • Anterior and rotational stability and Lysholm scores were not significantly different between groups • Postoperative loss of extension was significantly greater in knees with an extension angle >10° • Superficial graft laceration of the anteromedial bundle was observed significantly 	3

(continued)

TABLE 1 (continued)

Author(s), Year	Purpose	Study Design	Follow-up	Main Results	Level of Evidence
Webb et al, 2013 ⁵⁵	To investigate whether higher PTS is associated with increased risk for further ACL injuries after ACLR	<ul style="list-style-type: none"> • Patients with an extension angle <10° (n = 58) were compared with patients with an extension angle >10° (n = 42) • Prospective longitudinal study of 200 patients after sb ACLR, with follow-up data available for 181 patients • A lateral knee radiograph was used to measure PTS, defined as the angle between a line drawn tangentially to the medial tibial plateau and the proximal anatomic axis of the tibia • Data were analyzed for the association between the PTS and the incidence of further ACL injuries 	15 y	<p>more frequently during second-look arthroscopy in knees with an extension angle >10°</p> <ul style="list-style-type: none"> • Mean PTS was significantly higher in patients with further ACL injury than in those with no further injury • The odds of further ACL injuries after ACLR were increased by a factor of 5 among those with a PTS of ≥12° relative to those with a PTS <12° • Patients with a PTS ≥12° had a 59% incidence of further ACL injury compared with a 23% incidence for those with a PTS of <12° 	3
Li et al, 2014 ³²	To investigate the association between PTS and failure after ACLR	<ul style="list-style-type: none"> • From a database of 238 sb ACLR cases, 20 cases of failure were included and retrospectively compared with 20 randomly selected controls • Medial and lateral PTS were measured on MRI 	32.5 mo	<ul style="list-style-type: none"> • The medial PTS of the ACL-failure group was significantly higher than that of the control group (3.5° vs 6.1°) • The lateral PTS of the ACL-failure group was significantly higher than that of the control group (2.9° vs 5.5°) • The odds ratio of ACLR failure was 6.8 for medial PTS ≥5° relative to medial PTS <5° and was 10.8 for lateral PTS ≥5° relative to lateral PTS <5° 	3
Christensen et al, 2015 ⁹	To determine whether patients with a higher lateral PTS are at greater risk of early graft failure after ACLR	<ul style="list-style-type: none"> • Retrospective comparison of 35 patients with early failure (<2 y) of primary ACLR with 35 matched patients without failure of ACLR after a minimum of 4 postoperative years • Lateral PTS was measured on MRI 	6.9 y	<ul style="list-style-type: none"> • Patients with early graft failure had a significantly steeper lateral PTS than control patients (8.4° vs 6.5°) • No significant difference was observed when only male subjects were compared • The odds ratio for graft failure considering a 2° increase in lateral PTS was 1.6 and continued to increase to 2.4 and 3.6 for 4° and 6° increases in lateral PTS, respectively 	3
Li et al, 2014 ³³	To analyze the relationship between PTS and anterior tibial translation after sb ACLR	<ul style="list-style-type: none"> • Retrospective evaluation of 40 patients after sb ACLR • Medial and lateral PTS were measured on MRI, and patients were divided into 3 groups based on medial or lateral PTS (<3°, ≥3° to <5°, ≥5°) • Side-to-side differences in anterior tibial translation were measured using a KT- 	27.5 mo	<ul style="list-style-type: none"> • Both medial and lateral PTS statistically significantly correlated with anterior tibial translation • The group with a PTS ≥5° had significantly more cases of anterior tibial translation ≥5 mm than the group with a PTS <3° • The threshold for increased risk of anterior tibial 	3

(continued)

TABLE 1 (continued)

Author(s), Year	Purpose	Study Design	Follow-up	Main Results	Level of Evidence
Hohmann et al, 2010 ²⁵	To investigate the relationship between knee functionality and PTS after ACLR	<p>1000 arthrometer at 30° of flexion, and the results were stratified as ≤2 mm, >2 to <5 mm, and ≥5 mm</p> <ul style="list-style-type: none"> • 24 patients after sb ACLR • PTS was measured on digitalized lateral radiographs using the posterior tibial cortex as a reference • Patients were divided into 3 groups based on PTS: 0°-4° (n = 9), 5°-9° (n = 8), ≥10° (n = 7) • The Cincinnati scoring system was used to assess knee functionality 	21.1 mo	<p>translation ≥5 mm was a medial PTS >5.6° or a lateral PTS >3.8°</p> <ul style="list-style-type: none"> • No significant correlation between postoperative knee functionality and PTS was found • When patients were divided into subgroups according to PTS, a significant correlation between knee functionality and PTS was observed; patients with a higher PTS showed higher functional scores 	4

^aACLR, anterior cruciate ligament reconstruction; db, double-bundle; HTO, high tibial osteotomy; MAD, mechanical axis deviation; MRI, magnetic resonance imaging; OA, osteoarthritis; PTS, posterior tibial slope; sb, single-bundle.

(double and triple varus) were excluded from the study by Kim et al.²⁸ With regard to sagittal malalignment, the selected studies are more conclusive. Webb et al⁵⁵ found that the mean tibial slope was significantly greater in patients with ACL graft tear after ACLR compared with patients with no further injury. Patients with a tibial slope of 12° or higher had a 59% incidence of further ACL injury, compared with 23% for those with a tibial slope <12°. Li et al³² found significantly greater lateral slope and medial slope in patients with graft failure after ACLR, but the effect of the lateral slope was greater than that of the medial slope. Christensen et al⁹ also found a significantly steeper lateral slope in female patients with early graft failure but did not observe a significant difference in this parameter among male patients. In another study, Li et al³³ observed statistically significant correlations of the medial and lateral tibial slopes with postoperative anterior tibial translation after ACLR. Patients with a steeper medial or lateral slope showed a higher risk of anterior tibial translation of 5 mm or greater.

Posterior Cruciate Ligament, Posterolateral Corner, and/or Lateral Collateral Ligament. Three studies were identified, and all of them had level 4 evidence (Table 2). Summarizing the results of the 3 studies, varus malalignment must be regarded as a significant risk factor for failure after PCL and/or PLC reconstruction procedures.^{31,43,44} No selected clinical study analyzed the influence of the tibial slope on outcomes after PCL or PLC surgery.

Part B: Clinical Studies Investigating the Influence of Realignment Osteotomy With or Without Ligament Reconstruction on Postoperative Knee Function

Function of the ACL-Deficient Knee. A total of 11 studies were identified, and all of them had level 3 or 4 evidence

(Table 3). The stabilizing effect of isolated osteotomy on the ACL-deficient knee joint remains controversial. For example, Williams et al⁵⁶ reported that HTO alone had no effect on results of the Lachman test or pivot shift; however, 67% of patients receiving HTO alone reported a decrease in instability symptoms. Nevertheless, several studies have found significantly improved functional knee scores and stability after isolated valgus HTO, but procedures combining HTO with single-stage or 2-stage ACLR typically resulted in better outcomes.^{6,30,41,45} In patients undergoing combined HTO and ACLR, 2 studies have found that postoperative anterior tibial translation correlated with the postoperative tibial slope.^{14,60} For example, Dejour et al¹⁴ reported that the more the slope was increased during HTO, the greater the postoperative anterior tibial translation on unilateral weightbearing. In 2 studies, a second revision ACLR was performed in combination with anterior closing wedge slope-reducing HTO in patients with ACL graft failure in association with a posterior tibial slope of 12° or higher.^{13,52} Both studies reported that stability could be restored in all patients without significant loss of range of motion. Based on gait analysis, HTO combined with ACLR significantly decreased peak knee adduction moment and knee internal rotation moment, and these changes correlated with the decrease in static varus alignment.^{27,36}

Function of the PCL-, PLC-, and/or LCL-Deficient Knee. A total of 5 studies were identified, and all of them had level 4 evidence. The main findings of the analyzed studies are summarized in Table 4. There is agreement among the studies that realignment osteotomy can improve knee function and stability in PLC- and PCL-deficient knees. Based on the available evidence, valgus-producing medial open-wedge HTO can be considered an effective treatment method in patients with isolated or combined posterolateral instability and varus malalignment.^{4,6,40} Isolated

TABLE 2
Clinical Studies Investigating the Influence of Osseous Alignment on Postoperative Stability and Failure Rates After Reconstruction of the PCL, PLC, and/or LCL^a

Author(s), Year	Purpose	Study Design	Follow-up	Main Results	Level of Evidence
Noyes et al, 2006 ⁴⁴	To determine the factors responsible for failed PLC procedures	<ul style="list-style-type: none"> Retrospective analysis of 30 consecutive knees with 57 failed PLC procedures (13 acute and 17 chronic knee injuries) A comprehensive review of medical records, operative notes, radiographs, and MRI scans was conducted to determine factors that may have contributed to failure 	17 mo	<ul style="list-style-type: none"> Among all 57 failed PLC procedures, untreated varus malalignment was identified in 21 procedures (37%), or in 10 of 30 knees 	4
Noyes and Barber-Westin, 2005 ⁴³	To determine the factors contributing to failure after PCL reconstruction	<ul style="list-style-type: none"> Retrospective analysis of 52 failed PCL surgeries Medical records, operative notes, radiographs, and MRI scans were reviewed, and a comprehensive knee examination was conducted 	42 mo	<ul style="list-style-type: none"> Varus malalignment was identified in 16 procedures (31%) Varus malalignment was considered the sole factor contributing to failure in 1 procedure and as 1 of multiple factors contributing to failure in 15 procedures 	4
Lee et al, 2012 ³¹	To evaluate the reasons for failure of primary PCL reconstruction	<ul style="list-style-type: none"> Failure analysis of 22 patients undergoing revision PCL reconstruction for recurrent pathologic knee laxity after primary PCL reconstruction The probable cause of failure was retrospectively assessed by 2 orthopaedic surgeons 	36.3 mo	<ul style="list-style-type: none"> Varus osseous malalignment was a factor contributing to failure of primary PCL reconstruction in 9% of patients 	4

^aLCL, lateral collateral ligament; MRI, magnetic resonance imaging; PCL, posterior cruciate ligament; PLC, posterolateral corner.

open-wedge HTO has been shown to improve stability in several cases without the need for secondary ligament reconstruction. Whether increasing the tibial slope further improves outcome in these patients remains controversial.^{4,40} In patients with symptomatic hyperextension after failed PCL reconstruction, anterior open-wedge flexion HTO without revision PCL reconstruction has been shown to significantly improve knee function.⁴⁸

DISCUSSION

The most important findings of the present systematic review were that there is clinical evidence supporting osseous malalignment as a factor contributing to failure of knee ligament surgery and that realignment surgery can improve function and stability, especially in cases of PLC insufficiency and in combination with revision ACL surgery.

Valgus HTO is considered a well-established option for isolated unicompartmental degenerative joint disease and combined ligament instability. Its clinical value has been emphasized recently.^{34,57} Two recent systematic reviews have reported the results of valgus HTO in cases of knee instability,^{8,12} and another systematic review has reported the clinical outcomes of simultaneous HTO and ACLR.³⁴ However, these studies presented clinical and radiographic

outcomes in general without specifically analyzing the influence of osseous malalignment or realignment surgery on knee stability in detail. Less well understood is the influence of osseous alignment on ligament stability, especially the importance of the tibial slope. In many basic science studies, important roles of the tibial slope on ACL/PCL stability and of valgus alignment in LCL/PLC stability have been shown.^{††} However, the results of basic science studies are not easily translatable to the clinical setting.

Based on the findings of this systematic review, osseous alignment influences failure rates after ACLR. Several clinical studies (with level 3 evidence) showed an increased failure rate after ACL reconstruction among patients with a steep posterior tibial slope (PTS).^{9,32,33,55} Slope-reducing HTO appears to reduce the graft rupture rate and to increase knee stability in these cases. In particular, second revision ACLR appears to benefit from a reduced PTS through HTO.^{13,52} Reduced PTS and valgus may protect the reconstructed ACL from fatigue failure.¹³ Surgeons should therefore be especially aware of the potential impact of PTS on revision ACLR. In this regard, the surgeon should bear in mind that open-wedge HTO tends to increase the slope, whereas closed-wedge HTO tends to decrease the PTS.^{15,24} Unintentionally increased tibial slopes might play a role in

^{††}References 1, 18, 19, 21, 29, 47, 50, 51, 53, 54.

TABLE 3
Clinical Studies Investigating the Influence of Osseous Realignment With/Without Ligament Reconstruction on the Function of the ACL-Deficient Knee^a

Author(s), Year	Purpose	Study Design	Follow-up	Main Results	Level of Evidence
Noyes et al, 1993 ⁴¹	To compare the results of 3 different treatment modalities for younger patients with varus malalignment and chronic ACL deficiency	<ul style="list-style-type: none"> Retrospective evaluation of 41 patients with varus malalignment and chronic ACL deficiency treated via lateral closed-wedge HTO with or without additional stabilization procedures Three different procedures were compared: HTO alone (n = 11), HTO combined with a single-stage lateral iliotibial band extra-articular procedure (n = 14), and HTO combined with second-stage ACLR (n = 16) An intra- or extra-articular procedure was performed on patients with giving-way symptoms 	58 mo	<ul style="list-style-type: none"> All 3 groups showed significant improvements in the overall rating scores The HTO + extra-articular procedure group had significantly smaller increases in the overall rating scores than the HTO and HTO + ACLR groups Preoperatively, 54% of patients complained of giving-way during activity compared with 10% at follow-up The HTO + ACLR group had a significantly lower anterior laxity than the HTO + extra-articular procedure group Whereas 54% of patients had abnormally increased lateral joint opening preoperatively, this feature was found in only 12% at follow-up 	3
Dejour et al, 1994 ¹⁴	To analyze the results of patients undergoing simultaneous ACLR and HTO	<ul style="list-style-type: none"> Retrospective evaluation of 44 knees receiving single-stage ACLR and valgus HTO (lateral closed-wedge HTO in 37 knees and medial open-wedge HTO in 7 knees) for symptomatic chronic ACL rupture accompanied by varus malalignment 	3.6 y	<ul style="list-style-type: none"> 43 knees had a 2+ Lachman test score before the operation; at follow-up, the test results were negative in 16 knees and 1+ in 23 knees The mean anterior tibial translation was 10 mm preoperatively and 6 mm postoperatively Postoperative tibial translation correlated with the changes in PTS: the greater the increase in PTS after HTO, the greater the postoperative anterior tibial translation during unilateral weightbearing 	4
Lattermann and Jakob, 1996 ³⁰	To compare 3 different treatment options for patients with ACL deficiency, varus malalignment, and medial OA	<ul style="list-style-type: none"> 27 patients with chronic anterior instability, varus malalignment, and medial OA were evaluated retrospectively 3 groups of patients were compared: HTO alone (n = 11), HTO combined with 2-stage ACLR (n = 8), and HTO combined with single-stage ACLR (n = 8) The indication for treatment was based on symptoms and depended on pain, degree of instability, age, and amount of activity. High activity, a high degree of instability-related symptoms, and age <40 y were factors indicating 	5.8 y	<ul style="list-style-type: none"> Nineteen of 27 knees had a side-to-side difference of 3-5 mm on the Lachman test; no knees had a side-to-side difference of <3 mm on the Lachman test A difference of 3-5 mm on the Lachman test was found in 73% of patients after isolated HTO, in 75% after HTO combined with staged ACLR, and in 63% after HTO combined with single-stage ACLR A positive pivot-shift was found in 9 of 27 patients: in 18% of patients after isolated HTO, in 50% after HTO combined with staged ACLR, 	3

(continued)

TABLE 3 (continued)

Author(s), Year	Purpose	Study Design	Follow-up	Main Results	Level of Evidence
Badhe and Forster, 2002 ⁶	To report the results of ligament reconstruction with HTO in cases of ACL-, PCL-, and PLC ligament-deficient knees	<p>a combined treatment. The decision to perform a single- or 2-stage procedure depended on the severity of instability and the activity level.</p> <ul style="list-style-type: none"> • Open-wedge HTO was performed on 10 patients and closing-wedge HTO on 17 • Retrospective evaluation of 14 patients with ligamentous instability and varus malalignment treated with ligament reconstruction and HTO • 5 patients had a double-varus knee with ACL deficiency; all 5 were treated with single-stage closed-wedge HTO and ACLR • 9 patients had a triple-varus knee with PLC ligament injury (5 of these patients also had a PCL injury); of these patients, 6 were treated with LARS and the remaining 3 were treated with HTO alone • 4 patients with a triple-varus knee underwent open-wedge HTO and the remaining patients underwent closed-wedge HTO 	2.8 y	<p>and in 38% after HTO combined with single-stage ACLR; the same result was found for giving-way episodes</p> <ul style="list-style-type: none"> • The complication rate was highest among those receiving HTO combined with single-stage ACLR (63%) • At follow-up, 86% of knees were stable • Cincinnati Knee Rating Scale scores improved from a preoperative mean of 55 to a postoperative mean of 80 in patients receiving HTO + ACLR, from 49 to 65 in patients receiving closed-wedge HTO + PLC reconstruction, from 55 to 77 in patients receiving open-wedge HTO + PLC reconstruction, and from 57 to 76 in patients receiving HTO alone 	4
Williams et al, 2003 ⁵⁶	To evaluate the results of patients with ACL deficiency, symptomatic OA in the medial compartment, and varus malalignment treated with closed-wedge HTO alone or together with ACLR	<ul style="list-style-type: none"> • Retrospective evaluation of 26 patients with ACL deficiency, symptomatic OA in the medial compartment, and varus malalignment • 12 patients were treated with valgus closed-wedge HTO and 14 patients were treated with single-stage HTO combined with ACLR • Most patients treated with HTO alone suffered from medial joint-line pain without subjective instability, whereas patients treated with combined HTO and ACLR reported pain and instability 	45.8 mo	<ul style="list-style-type: none"> • HTO alone had no effect on the Lachman test results or on pivot shift, but 67% of patients reported a decrease in instability symptoms • HTO + ACLR resulted in a grade 1 score on the Lachman test in 11 of 13 patients and a negative pivot shift in 12 of 13 patients • 92% of patients were able to participate in recreational sports postoperatively compared with 56% preoperatively. The Lysholm knee score was good/excellent in 25% of patients after HTO alone and in 69% after HTO + ACLR 	4
Zaffagnini et al, 2013 ⁶⁰	To evaluate the clinical and radiographic outcomes after sb over-the-top ACLR and concomitant lateral closing-wedge HTO in patients with varus angulated ACL-deficient knees	<ul style="list-style-type: none"> • Prospective case series of 32 patients who underwent sb over-the-top ACLR and concomitant lateral closing-wedge HTO for chronic ACL deficiency, varus malalignment, and initial medial OA 	6.5 y	<ul style="list-style-type: none"> • All scores significantly improved from preoperatively to the final follow-up • Measurement using the KT-1000 arthrometer showed a mean side-to-side difference of 2.2 mm 	4

(continued)

TABLE 3 (continued)

Author(s), Year	Purpose	Study Design	Follow-up	Main Results	Level of Evidence
Noyes et al, 2000 ⁴⁵	To evaluate the outcome of operative treatment in patients with ACL deficiency and double- or triple-varus knee syndromes	<ul style="list-style-type: none"> • 60% underwent primary ACLR, and 40% underwent revision ACLR • At final follow-up, the mechanical axes crossed the tibial plateau at a mean of 56% and PTS decreased by a mean of 1.2° relative to preoperatively • Prospective evaluation of 41 patients undergoing surgical treatment for ACL deficiency, varus malalignment, and partial to complete lateral ligament deficiency • All patients were treated with closed-wedge HTO, and 34 patients underwent ACLR a mean 8 months later. Posterolateral reconstruction was also performed on 18 knees (triple-varus knees) • Gait tests were conducted on 17 knees (12 double-varus and 5 triple-varus knees) before and after HTO 	4.5 y	<ul style="list-style-type: none"> • Two patients had pathological anterior laxity >5 mm (failure rate of 6%) • A significant positive correlation between postoperative PTS and anterior tibial translation was found • Preoperatively, all patients with double-varus knees (n = 23) had an abnormal increase in lateral joint opening (mean, 4 mm); at follow-up, no patient had a >2 mm increase in lateral joint opening • Preoperatively, all patients with triple-varus knees (n = 18) had an abnormal increase in lateral joint opening (mean, 8 mm) and an increase in external tibial rotation (mean, 9°); at follow-up, 14 knees had a <3 mm increase in lateral joint opening and a <5° increase in external tibial rotation • At follow-up, the reconstructed ACL was functional in 42% of patients, was partially functional in 24%, and had failed in 33%; 67% of all failures were revision cases. • Elimination of giving-way was reported in 85% of cases • Mean adduction moment decreased below normal values postoperatively 	4
Kean et al, 2009 ²⁷	To evaluate the effects of simultaneous HTO and ACLR on 3-dimensional gait patterns and muscle activity	<ul style="list-style-type: none"> • 21 patients with varus malalignment, medial OA, and ACL deficiency were tested before and 1 year after single-stage medial open-wedge HTO and ACLR • 3-dimensional gait analysis data were used to calculate external coronal and sagittal moments of the knee • EMG data were used to calculate muscle activity 	12 mo	<ul style="list-style-type: none"> • Neutral alignment and knee stability were achieved in all patients • Peak knee adduction moment and early stance flexion moment significantly decreased, and late-stance knee extension moment significantly increased • Muscle activation patterns did not change significantly 	4
Marriott et al, 2015 ³⁶	To investigate changes in gait biomechanics after combined medial open-wedge HTO and ACLR	<ul style="list-style-type: none"> • 33 patients with varus malalignment, OA in the medial compartment, and ACL deficiency completed 3-dimensional gait analysis preoperatively and at 2 and 5 y after combined ACLR and medial open-wedge HTO 	68 mo	<ul style="list-style-type: none"> • In the surgical limb, there was a significant decrease in the peak knee adduction moment from preoperative to 2 years postoperative, without a significant change from 2 to 5 y postoperative 	4

(continued)

TABLE 3 (continued)

Author(s), Year	Purpose	Study Design	Follow-up	Main Results	Level of Evidence
Sonnery-Cottet et al, 2014 ⁵²	To evaluate the clinical outcome of combined re-revision ACLR and proximal tibial anterior closing-wedge osteotomy in patients with recurrent graft failure in association with increased PTS	<ul style="list-style-type: none"> Retrospective evaluation of 5 patients who underwent single-stage re-revision ACLR and proximal tibial anterior closing-wedge osteotomy to reduce the PTS All patients had at least 2 previous ACLRs, and failure of the ACL graft was associated with an excessive PTS ($\geq 12^\circ$) in all cases 	31.6 mo	<ul style="list-style-type: none"> Decreases in the peak knee flexion moment and peak knee internal rotation moment were also observed Relatively large correlations of the decrease in static varus alignment with the decreases in knee adduction moment and in knee internal rotation moment were observed Mean PTS was corrected from 13.6° preoperatively to 9.2° postoperatively Knee stability and function were restored in all patients The mean side-to-side differential anterior laxity was 10.4 mm preoperatively and significantly decreased to 2.8 mm postoperatively 	4
Dejour et al, 2015 ¹³	To evaluate the outcome of second revision ACLR combined with tibial deflexion osteotomy for correction of excessive PTS	<ul style="list-style-type: none"> Retrospective evaluation of 9 patients who underwent single-stage second-revision ACLR combined with tibial deflexion osteotomy (anterior closing-wedge HTO) to decrease the PTS All patients had 2 previous ACLR failures and a PTS $\geq 12^\circ$ 	4.0 y	<ul style="list-style-type: none"> The mean PTS was corrected from 13.2° preoperatively to 4.4° postoperatively All patients had stable knees The mean side-to-side anterior tibial translation decreased from 11.7 mm preoperatively to 4.3 mm postoperatively Compared with the healthy contralateral knee, all injured knees regained full range of motion without recurvatum 	4

^aACLR, anterior cruciate ligament reconstruction; db, double-bundle; HTO, high tibial osteotomy; LARS, Ligament Advanced Reconstruction System; MRI, magnetic resonance imaging; OA, osteoarthritis; PCL, posterior cruciate ligament; PLC, posterolateral corner; PTS, posterior tibial slope; sb, single-bundle.

the increased incidence of ACL ruptures.¹⁷ Hinterwimmer et al²³ highlighted the use of sagittally placed Kirschner wires to perform the appropriate amount of correction in open-wedge HTO.

Regarding primary ACLR, the evidence in the current literature is not conclusive, but there is a trend toward a relevant effect of posterior slope reduction on ACLR success. However, the absolute amount of slope reduction necessary is presently unknown. Coronal plane correction in primary varus knees is probably not necessary to achieve knee stability²⁸; however, in double or triple varus knees, basic science studies have shown increased strain on the ACL, which may cause the reconstructed ACL to fail.^{22,53} Additionally, correction of associated varus or valgus malalignment protects the joint from further degeneration.

In contrast to the ACL, in which clinical studies have shown an influence of the tibial slope on failure rates, little clinical data regarding the PCL are available.^{31,43} Noyes and Barber-Westin⁴³ investigated the failure mechanism of 52

PCL-reconstructed knees and found that varus malalignment contributed to failure in 31% of cases. However, no detailed analysis of the tibial slope was performed. Again, Noyes et al,⁴⁴ in another analysis of failure in 57 consecutive posterolateral operative procedures, showed that untreated varus malalignment contributed to failure in 37% of cases. Regarding this high failure rate, it is currently understood that in cases of posterolateral instability and severe varus alignment, the varus malalignment should be corrected either before ligament stabilization or as a combined procedure. In this study, the role of the tibial slope in ligament stability has not been investigated. Reichwein and Nebelung⁴⁸ investigated 15 cases of high tibial slope-increasing osteotomy for revision of PCL instability. They found a significant improvement in International Knee Documentation Committee scores in this challenging group of patients. Naudie et al⁴⁰ investigated 16 patients (17 knees) with symptomatic hyperextension-varus thrust treated via open-wedge HTO. Four patients had a PCL injury, 7 a combined PCL

TABLE 4
Clinical Studies Investigating the Influence of Osseous Realignment With/Without Ligament Reconstruction on the Function of the PCL-, PLC-, and/or LCL-Deficient Knee^a

Author(s), Year	Purpose	Study Design	Follow-up	Main Results	Level of Evidence
Badhe and Forster, 2002 ⁶	To report the results of ligament reconstruction with HTO in cases of ACL-, PCL-, and PLC-deficient knees	<ul style="list-style-type: none"> Retrospective evaluation of 14 patients with ligamentous instability and varus malalignment treated with ligament reconstruction and HTO 5 patients had a double-varus knee with ACL deficiency; all of these patients were treated with single-stage closed-wedge HTO and ACLR 9 patients had a triple-varus knee with PLC injury (5 also had a PCL injury); of these patients, 6 were treated with LARS, and the remaining 3 were treated with HTO alone 4 patients with triple-varus knees underwent open-wedge HTO and the remaining patients underwent closed-wedge HTO 	2.8 y	<ul style="list-style-type: none"> At follow-up, 86% of knees were stable Cincinnati Knee Rating Scale scores improved from a preoperative mean of 55 to a postoperative mean of 80 in patients receiving HTO combined with ACLR, from 49 to 65 in patients receiving closed-wedge HTO combined with PLC reconstruction, from 55 to 77 in patients receiving open-wedge HTO combined with PLC reconstruction, and from 57 to 76 in patients receiving HTO alone 	4
Naudie et al, 2004 ⁴⁰	To assess the functional outcome of medial open-wedge HTO in patients with posterolateral instability and hyperextension-varus thrust	<ul style="list-style-type: none"> The results of 17 open-wedge HTO procedures in 16 patients were retrospectively evaluated All patients had posterolateral instability with symptomatic hyperextension-varus thrust The etiology of the instability was an isolated PCL injury in 4 patients, a combined PCL and PLC injury in 7 patients, and capsuloligamentous laxity in 5 patients After HTO, coronal alignment was changed to a mean of 6° valgus, and the PTS was increased by a mean of 8° 	56 mo	<ul style="list-style-type: none"> All patients had significant improvements in their Tegner and Lysholm scores All patients felt that knee stability had improved with HTO All patients except 1 were satisfied with the surgery and would undergo the procedure again 5 patients underwent delayed ligament reconstruction (3 patients underwent PCL reconstruction, 1 underwent combined ACL and PCL reconstruction, and 1 underwent combined PCL and PLC reconstruction) 	4
Arthur et al, 2007 ⁴	To assess the functional outcomes of patients with grade 3 posterolateral instability and varus malalignment treated with open-wedge HTO	<ul style="list-style-type: none"> Prospective observation of 21 patients with chronic PLC deficiency and varus malalignment initially treated with open-wedge HTO Isolated PLC deficiency was present in 7 patients, 6 patients had ACL and PLC deficiency, 6 patients had PLC and PCL deficiency, and 2 patients had PLC, PCL, and ACL deficiency 	37 mo	<ul style="list-style-type: none"> In 38% of patients, second-stage ligamentous reconstruction was not necessary Isolated PLC injuries required second-stage ligamentous reconstruction in 33% of cases compared with 71% of multiligament knee injury cases Low-velocity sports-related injuries required second-stage ligamentous reconstruction in 40% of cases compared with 78% of high-velocity motor vehicle injury cases 	4

(continued)

TABLE 4 (continued)

Author(s), Year	Purpose	Study Design	Follow-up	Main Results	Level of Evidence
Ayerza et al, 2012 ⁵	To investigate the functional outcome of open-wedge osteotomy of the lateral tibial plateau in patients with posterolateral rotatory instability due to depression of the lateral tibia plateau	<ul style="list-style-type: none"> The mechanical axis point was changed by HTO from 26.7% to 57.5%; PTS was not significantly altered by HTO Second-stage ligamentous reconstruction was performed on patients with continued instability after HTO 	5.4 y	<ul style="list-style-type: none"> Final postoperative Cincinnati Knee Rating scores were significantly lower in patients treated with second-stage ligamentous reconstruction At final follow-up, no patient had symptomatic posterolateral instability Stability testing revealed no differences compared with the opposite side 	4
Reichwein and Nebelung, 2007 ⁴⁸	To assess the functional outcome of flexion HTO in patients with symptomatic hyperextension after failed PCL reconstruction	<ul style="list-style-type: none"> Prospective evaluation of 7 patients with failed PCL reconstruction and symptomatic hyperextension treated with anterior open-wedge flexion HTO (combined with varization in 4 patients) The mean PTS was altered from 4° preoperatively to 11.4° postoperatively, with a mean increase of 6.6° 	20 mo	<ul style="list-style-type: none"> Subjective and objective IKDC scores were improved postoperatively in all patients Second-stage revision PCL reconstruction was performed on 3 patients but only marginally improved the results 	4

^aACL, anterior cruciate ligament; ACLR, anterior cruciate ligament reconstruction; HTO, high tibial osteotomy; IKDC, International Knee Documentation Committee; LARS, Ligament Advanced Reconstruction System; LCL, lateral collateral ligament; PCL, posterior cruciate ligament; PLC, posterolateral corner; PTS, posterior tibial slope.

and PLC injury, and 5 a capsuloligamentous laxity. After a mean follow-up period of 56 months, the Tegner and Lysholm scores and the 5-point visual analog scores for knee stability and satisfaction were assessed. In addition, radiographs were analyzed to determine changes in femorotibial and mechanical axis alignment, tibial slope, and patellar height. In all patients, the Tegner and Lysholm score significantly improved after HTO. However, 30% of patients showed persistent instability and underwent a secondary PCL reconstruction to restore posterior stability. The authors concluded that open-wedge HTO is a good treatment for select patients with a symptomatic varus thrust. Arthur et al⁴ prospectively investigated 21 patients with combined grade 3 posterolateral instability and varus deformity. Patients were either treated with medial-opening HTO and second-stage ligament reconstruction (62%) or with HTO alone (38%). The mean follow-up duration was 37 months. In 38% (8/21) of patients, second-stage PLC reconstruction was not necessary because the outcome had been sufficiently improved by HTO. The authors concluded that medial open-wedge HTO is an effective first method of treatment for patients with varus knees and chronic combined posterolateral knee injuries.

Surgical correction of osseous alignment also has upper limits, beyond which no further correction should be made.

We recommend that correction of the tibial slope should not lead to hyperextension greater than 5° in cases of ACL surgery or 0° of extension in cases of PCL surgery because knee function would otherwise be compromised.

Limitations

Regarding these complex cases, there is still a lack of high-quality clinical studies. Nearly all included studies had level 3 or 4 evidence. Only 1 study with level 2 evidence could be included. For the rare cases of PCL/PLC/LCL instability, only level 4 evidence was available. Given the heterogeneity in the study design, patient selection, and surgical techniques, no quantitative comparison across studies or meta-analysis was possible. However, since a total of 28 clinical studies could be included, several recommendations for clinical work were generated (level 3 evidence).

Furthermore, measuring the tibial slope on radiographs is occasionally difficult, and multiple measurement methods exist, although they produce different normal values.¹⁷ Commonly used methods for measuring coronal alignment and the tibial slope on radiographs are displayed in Figure 2. Magnetic resonance imaging (MRI) techniques enabling independent measurement of the medial and

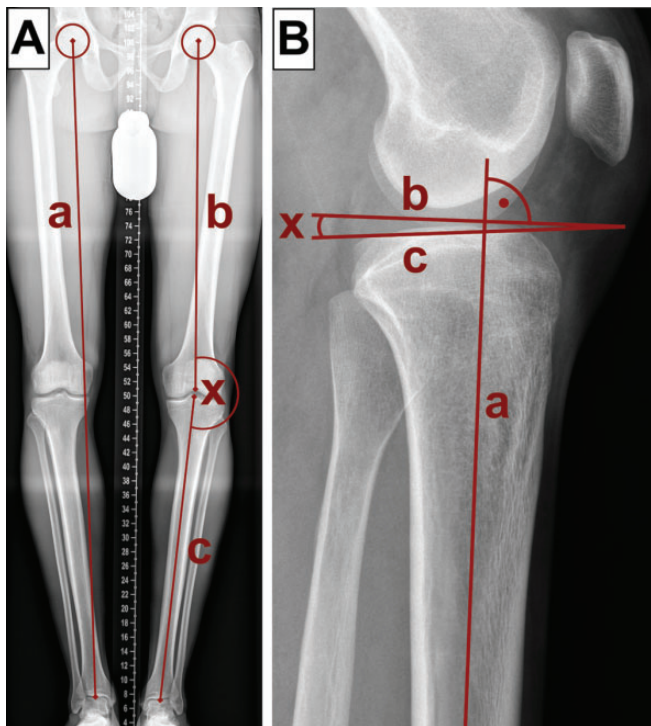


Figure 2. (A) Coronal alignment is analyzed using the weight-bearing line of the lower limb (a) and the mechanical tibiofemoral angle (x), which is defined as the angle between the mechanical axes of the femur (b) and tibia (c), respectively. (B) The tibial slope is defined as the angle (x) between a line (b) perpendicular to the proximal anatomical axis of the tibia (a) and a tangent along the tibial plateau (c).

lateral tibial slopes have been described but have only rarely been used to date.²⁶ Some studies measured the medial and lateral tibial slopes independently while others did not. To improve future research and to make studies comparable, a uniform method to measure the tibial slope should be defined. In general, long lateral knee radiographs should be preferred over short radiographs.¹⁶ If MRI is used, the circle method described by Hudek et al²⁶ may be the preferred method since it has been shown to be the most repeatable method.³⁵

CONCLUSION

When treating cases of knee instability, the 3-dimensional osseous alignment of the knee should be analyzed. Basic parameters warranting analysis include the mechanical weightbearing axis and the tibial slope. Although no recommendations for realignment procedures in primary ACLR are currently available, in revision cases, changes in the tibial slope should be considered, and correction of abnormal slope is recommended in cases of the multiply revised ACL (level 3 evidence). In contrast, in cases of PLC instability, osseous correction of a varus thrust is often the first step in treatment, occasionally rendering secondary ligamentous stabilization unnecessary (level 4 evidence).

Recommendations for the PCL regarding the tibial slope cannot be drawn from the clinical literature, but beneficial effects are suspected based on basic science studies. No clinical data are available for medial-sided knee instability or osseous alignment. Changes in the mechanical axis should be considered in all cases of knee instability together with early unicompartmental osteoarthritis. Future studies should focus on the amount of slope correction and whether slope correction plays a role in primary ACLR. Furthermore, the quality of future studies should be improved, especially by including control groups and randomizing treatment.

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