Archives of Orthopaedic and Trauma Surgery (2026) 146:14
https://doi.org/10.1007/s00402-025-06162-7

RESEARCH

Individualized indication for slope changing osteotomy in ACL insufficiency: the Avalanche Concept

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Received: 20 November 2025 / Accepted: 9 December 2025
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Abstract

The management of increased posterior tibial slope (PTS) in anterior cruciate ligament (ACL) injuries and insufficiencies and especially the indication for slope changing osteotomies has evolved to a highly discussed topic. The majority of available studies refer to cut-off values for the PTS and the number of previous ACL reconstructions in their indications. However, ACL injuries are a complex multifactorial problem, and available recommendations mainly ignore these highly individual factors, in their presence, and also in their complexity. Actually, many of the known risk factors for ACL insufficiency are also directly or indirectly associated with PTS. Therefore, the purpose of this paper is to propose a whole new way of thinking about complex ACL treatment strategies by integrating the PTS in a comprehensive approach of individual risk assessment and decision making. It is inspired by an established risk stratification system in a completely different but also very comparable field: avalanches. It is ultimately based on the thorough analysis of individual risk factors and accompanying circumstances on the one hand, and the standardized measured PTS on the other hand. These then define a point on a heat map (in a coordinate system) which, through the underlying colour, reflects the strength of the recommendation for a slope correction. This is to introduce *The Avalanche Concept*.

Keywords ACL · Slope · Osteotomy · Reconstruction · Revision · Tibia

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Introduction

In recent years, the management of increased posterior tibial slope (PTS) in anterior cruciate ligament (ACL) injuries and insufficiencies has evolved to a highly discussed topic. The reported influence of the PTS on the results and especially failure rates of ACL reconstructions makes it impossible to ignore this bony risk factor [1–4]. However, there is still only little evidence with regard to slope-changing osteotomies, especially regarding indications: Almost all available clinical studies are small case series without control groups; even fewer report on medium term results, and no long-term results have been reported yet [5–11].

Therefore, it is absolutely necessary to bridge the gap between harsh reality and lack of evidence with modern treatment concepts: Concepts that take the PTS into account as one relevant factor among others and that can be applied to the individual patient-specific case. Concepts that allow modifications to account for increasing evidence and future research.

Therefore, the purpose of this paper is to propose a whole new way of thinking about complex ACL treatment strategies

Published online: 23 December 2025

by integrating the PTS in a comprehensive approach of individual risk assessment and decision making. This concept has been applied regarding individualized therapy decisions at the authors' institutions for years but has not been comprehensively published yet [12, 13]. It is inspired by an established risk stratification system in a completely different but also very comparable field: avalanches.

Therefore, this is to introduce *The Avalanche Concept.*

Principle considerations

Understanding the PTS: why threshold values are misleading

Large parts of the literature available on slope changing surgery repeatedly refer to 12° as a 'threshold value', suggesting that there is an erratic increase in the risk of ACL re-injury from this value upwards [7, 8, 11, 14]. However, this interpretation does not reflect reality and is misleading: The proposed 12° originate from studies analyzing ACL failure rates and then defining a cut-off value in a purely mathematical model with the inherent aim to form two groups [3, 4, 15, 16].

But the reality is different on all levels: Biomechanically the forces acting on the ACL increase approximately linearly with increasing slope [17–19]. This is in line with basic physical considerations regarding 'gravity on inclined planes': the downhill slope force (corresponding to the force on the ACL) correlates with the degree of the inclination (=PTS). In physical calculation it is the product of the gravitational force and the sine of the angle α of the inclination ($F = F_{grav} \times \sin(\alpha)$). And within the range of 0° to 25° (typical PTS range) a sine curve is almost linear. In particular, even clinical studies have demonstrated an almost linear relationship between the PTS and ACL reconstruction failures [15, 20]. Additionally, regarding the practical interpretation of published case series, it must be noted that the very same supposed 'cut-off value' was frequently reported, even though different measurement methods were used.

The difference of measured values is primarily related to the tibial axis that is used as reference, and it has been proven that these measurements differ significantly from one another [21]. So, how reasonable can a single threshold be for different measurement methods?

It must be concluded that defining a single threshold value can neither be adequate nor sufficient. Conclusively, considerations must be based on a constant, approximately linear relationship between the PTS and the resulting risk.

Understanding risk factors for ACL injury: many are related to the PTS

ACL injures and even more re-injuries are complex multifactorial events with multiple other conditions and risk factors apart from the PTS [22–25]. Various factors are playing a key role in the strategy of every single ACL revision even without considering the PTS. Nevertheless, recent literature shows that many of these factors are either directly or indirectly related to the PTS—especially in the setting of ACL injury or insufficiency. Therefore, these factors must be comprehensively considered separately and additionally in relation to the PTS.

The factors and conditions to be considered are not limited to actually measurable or determinable (yes/no) parameters, but include also specifical an individual evaluation of qualitative parameters, e.g. how the quality of previous reconstructions has been, how well and for how long an ACL reconstruction has actually worked, or factors like family history and intended sports levels.

Table 1 provides an overview of reported individual factors that are related or connected to the PTS, and how these might be of relevance in the decision for or against a bony correction. It must be noted that there are conditions that ultimately necessitate even more individualized treatment strategies, e.g. medial or lateral instabilities in varus or valgus aligned knees. Therefore, these are deliberately excluded here.

With regard to the PTS itself it is essential to be aware of the prevalence of different slope values: a PTS of ≥ 12° (according to the proximal anatomical axis as proposed by Dejour and Bonnin) is a generally not uncommon condition which is present in more than 32% of ACL injuries, 35% of ACL revisions, 45% of multiple ACL revision cases, and even 20% of healthy controls—with significant differences between ethnic groups [12, 42, 45, 46]. If all of these would be treated as pathological and subsequently be corrected an enormous and inadequate number of osteotomies would result against the background of the overall satisfying results in the majority of revision ACL reconstructions [44, 47, 48]. This again demonstrates the necessity of taking other factors into account.

Understanding risk interpretation and treatment goals: why a scoring system is not an option

In scenarios where various factors have to be considered, the idea might arise to simplify risk stratification using a score and then base the clinical decision in either yes or no on the resulting final score. However, the use of a defined score massively underestimates the overall complexity even if the

Table 1 Factors and conditions influencing individual ACL insufficiency and their implication in the decision whether slope-decreasing osteotomy might be indicated

Factor or condition	Influence and evidence	Consequence
High-grade instability with distinct anterior tibial translation (ATT)	High degrees of instability, especially with excessive ATT and greater static anterior subluxation of the tibia have been shown to be associated with a high PTS [26, 27]. High-grade instabilities have been shown to have a higher failure rate in ACL reconstruction [2, 20, 25]. An increased risk of failure for revision ACL reconstructions has been shown in cases with pre-existing high-grade instabilities [28] The presence of additional anteromedial and/or anterolateral instabilities might additionally increase this effect.	Osteotomy might rather be considered in the presence of pronounced instability
Meniscus ramp lesions, medial and lateral root tears and meniscus deficiency	Ramp lesions as well as medial and lateral posterior root tears have been shown to be associated with higher PTS [29–33]. It might be assumed that the extent and severity of the lesion also play a role. This should therefore also be taken into account. It is unclear if a change in PTS might influence the result of these meniscus repairs.	Osteotomy might be considered more in the presence of meniscus lesions or deficiency, especially in severe injury patterns and chronic cases
Chronicity	Chronic ACL insufficiency might lead to changes in laxity of the whole joint capsule and periphery with subsequent higher grades of instability [34, 35].	Osteotomy might be considered more in chronic than in acute cases
Type of injury	Non-contact injuries have been shown to be more frequently associated with a high PTS than contact injuries [36].	Osteotomy should be considered more in non-contact injuries
Trauma mechanism	An inadequate trauma mechanism or graft failure without trauma may be a sign of chronic overload, spontaneous failure without other obvious causes, or what is sometimes referred to as biological failure [37].	Osteotomy should be considered more in inadequate trauma mechanisms
Number of previous ACL reconstructions	Repeated graft failures are highly correlated with a high PTS [12, 15].	Osteotomy might be considered more the more previous ACL reconstructions have been performed
Quality of previous ACL reconstructions	An ACL reconstruction might fail because of inadequate reconstruction, non-anatomic tunnel placement or technical errors within the previous surgery [25]. In these cases, the PTS might not be the decisive factor. In particular, when patients report that an ACL reconstruction was never successful after surgery, it is not unlikely that technical errors were present.	Osteotomy might be considered more if previous ACL reconstructions have been performed technically correct
Previous LET or anterolateral reconstruction	An additional LET or anterolateral reconstruction appears to relatively reduce the risk of further ACL injury in all slope conditions, although high failure rates have been reported in elevated slope conditions, especially in combination with distinct static anterior translation [20, 38] In cases without previous LET or anterolateral reconstruction an ACL revision with adding these might be sufficient without considering osteotomy based on individual factors.	Osteotomy might be considered more in cases with previously performed LET or anterolateral reconstructions
Time since previous ACL reconstruction(s) and functional level since	A significant correlation has been reported between PTS and time to graft insufficiency [12, 15]. Generally, a longer time period and a high functional level since the preceding ACL reconstruction indicate that an ACL reconstruction worked well as intended, despite a high PTS may have been present.	Osteotomy might be considered less if previous ACL reconstructions had good function over longer time periods
Age	Age is generally seen as a risk factor for ACL injury as well as subsequent re-injuries [23, 24, 39–41]. This reflects the fact that the many individual risk factors and the resulting individual risk constellation can lead to ACL injury already early in life.	Osteotomy should be considered more in patients of younger age
Sex	No difference has been reported between males and females with regard to the radiologically measured PTS [42]. Repeated graft insufficiencies are seen more often in males [12, 15, 40].	Osteotomy should be considered independent of gender
ACL injury of the contralateral side	Contralateral ACL rupture is a strong independent risk factor for further ACL injuries [39]. Patients with bilateral ACL reconstructions have been reported to have a higher PTS compared to patients with unilateral ACL injury [43].	Osteotomy might be considered more in cases with bilateral ACL injuries

Table 1 (continued)

Factor or condition	Influence and evidence	Consequence
Family history	A family history of ACL ruptures is an independent risk factor for ACL injuries, and might be seen as an expression of the fact that several hereditary factors lead to an overall increased risk [25].	Osteotomy might be considered more when a family history of ACL injuries and especially re-injuries is present
Sports level	High rates of return-to-preinjury-level and overall high Tegener activity scale have been reported in cases of primary ACL reconstruction with PTS correction [10]. Comparable return-to-sports-rates have been reported for 3rd ACL reconstruction with osteotomy compared to revision ACL reconstructions without osteotomy [11, 44]. Return-to-sports rate and especially the achievable sport level seems to be mainly determined by the general condition and the previous history of the knee, and less by the osteotomy itself. No data is available on professional athletes.	High sports level does not seem to be a contraindication for osteotomy Osteotomy in professional athletes should be indicated very cautious, reserved and highly individual
Hyperextension and general laxity	General laxity is often related to hyperextension. Pre-existing hyperextension is likely to further increase after slope-decreasing osteotomy. The resulting increase of hyperextension after osteotomy is usually not equivalent to the amount of slope correction, and even postoperative hyperextension has been reported to be usually asymptomatic [11]. However, distinct hyperextension and recurvatum with impaired function can be a serious problem. Additional procedures to prevent overall hyperextension by creating an intraarticular extension deficit to counteract the bony correction should be seen extremely critical.	Hyperextension is not a strict contraindication for osteotomy, but cases with pre-existing hyperextension and larger corrections should be carefully evaluated. A controlled correction to a different target value may be discussed

ACL anterior cruciate ligament, *LET* lateral extraarticular tenodesis, *PTS* posterior tibial slope, *ATT* anterior tibial translation

PTS is additionally considered. This might consequently be seriously misleading for various reasons:

- Oversimplification: Complex factors (e.g. meniscus status) would be reduced to either yes or no, not taking into account their severity, significance or pathogenesis ('linearization of complex factors'). Further, qualitative factors (e.g. quality of previous reconstructions) cannot be reasonably quantified. Interrelations between individual factors are lost: some factors mutually reinforce each other when they coincide and cannot be adequately represented with a sum of points.
  Ultimately, extremely subtle differences can lead to a completely different treatment decision, as a half a degree higher PTS or one point of a factor with minor relevance might completely change the treatment decision.
- Illusion of precision: Score items appear objective, but are simply arbitrary. Neither the respective significance of the individual factors nor, in particular, their interaction between each other has been clearly and coherently investigated. The individual weighting of factors would be highly subjective.
- Lack of evidence: A system that ultimately produces a definitive yes-or-no result needs to be based on a broad range of existing evidence. In this field, the available data is nowhere near sufficient to justify a clear decision.
- Treatment goals, surgeon's and patient's perspectives: Discussion on slope corrections usually involves the likelihood of suffering a re-rupture as key parameter. Neither can a slope correction prevent this in 100% of the cases, nor does ligamentous reconstruction alone without osteotomy fail in the majority of cases. For the patient, the ultimate consideration is whether a potential reduction in risk from X to Y% justifies the additional surgery and associated risks. From the surgeon's point of view, this is essentially the 'number needed to treat' – to possibly prevent one re-rupture. For the patient it is the decision whether the achievable risk reduction and benefits are worth to take the potential risks, larger surgical procedure and potential adverse effects. Ultimately, it is therefore a highly individual decision, and a score value in a sense disempowers the patient, as it predetermines the outcome of this decision.

Understanding risk stratification in avalanches

Avalanches represent a significant, often life-threatening danger in all areas of alpine sports, especially skiing, ski touring and freeriding and on point assessment is crucial to prevent severe incidents [49]. Modern assessment concepts are based on the work of Swiss mountain guide Werner Munter in the 1980s [50]. Ultimately, the risk of an avalanche occurring is based on a combination of various

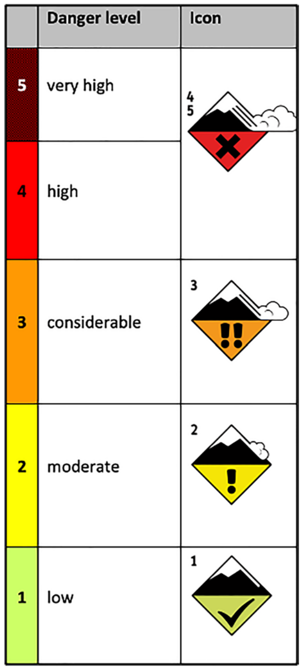

Fig. 1 The European Avalanche Danger Scale (permission: European Avalanche Warning services, avalanches.org)

factors, some of which are predetermined, some of which can vary and change, and some of which represent individual factors related to the skier:

The overall situation is usually reported in an avalanche bulletin issued by the competent authorities using a risk scale (Fig. 1) taking particularly into account weather conditions such as the amount and type of snowfall and fresh snow, wind strength, temperatures and solar radiation. In addition, further assessment of local parameters must be considered for the specific situation, such as actual exposure, terrain conditions, altitude and terrain shape. It is absolutely essential to know or measure the steepness of the terrain, as the slope gradient is crucial for the probability of an avalanche occurring: in low slope gradients, the probability of triggering an avalanche is minor. Last but not least, the skier himself must also be taken into account, with his individual abilities and experience. To aid the decision-making process, researchers and avalanche experts have developed different decision-making frameworks (DMFs). One of them is the so-called *SnowCard* developed by Engler et al., distributed by the German Alpine Association (Deutscher Alpenverein, DAV) [51]. In Fig. 2 the *SnowCard* is displayed and its practical application is explained.

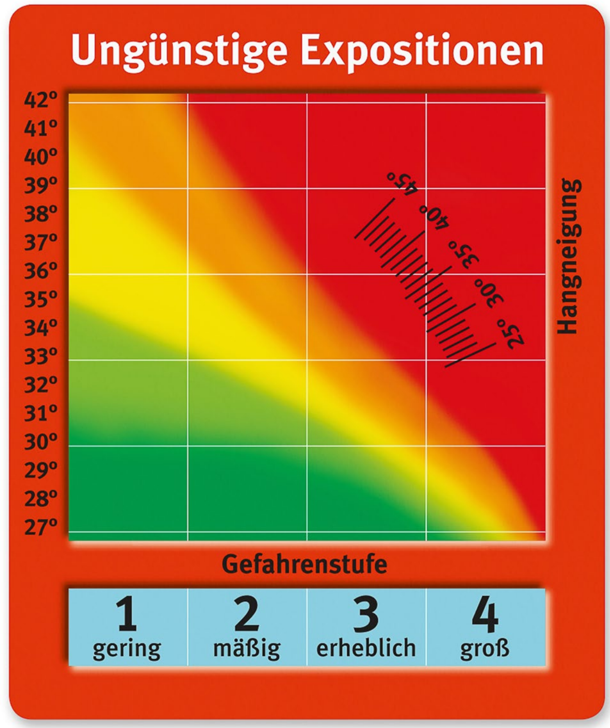

Fig. 2 The *SnowCard* of the German alpine association: In practical application, the warning levels (=Gefahrenstufe) from the avalanche bulletin are plotted on the x-axis, and the presence of additional risk factors lead to a position further to the right or left within the warning level. The slope gradient in the individual situation is plotted on the y-axis. The underlying colour of the intersection of the two defines the risk of triggering an avalanche. The final decision on whether to put oneself in danger and ski down the slope in question is made by the skier themselves. (Translation: *Hangneigung*=Slope, *Gefahrenstufe*=Danger Level, Level 1–4 refer to low, moderate, considerable, high. The title (*Ungünstige Expositionen)* refers to the use of this card in terrain with unfavourable expositions). The scale from 25° to 45° is an additional tool for measurement of the slope when in the terrain. (permission: Jan Mersch)

The Avalanche Concept

The *Avalanche Concept* for individualized indication of slope changing osteotomies transfers the established risk stratification principles and the decision-making frameworks in avalanches to knee surgery: It combines the individual risk assessment of specific factors (in their presence, quantity and quality) with the standardized measured PTS (which corresponds to the steepness of the terrain) to display the individual risk on a heat map, and thus define the degree of recommendation for a slope changing osteotomy. It serves as a decision-guidance tool, but ultimately leaves the individual decision to the patient and the surgeon in the respective case.

Thereby it overcomes the oversimplified approach using a strict threshold of the PTS or simply counting the number of previous ACL reconstructions. It must be acknowledged

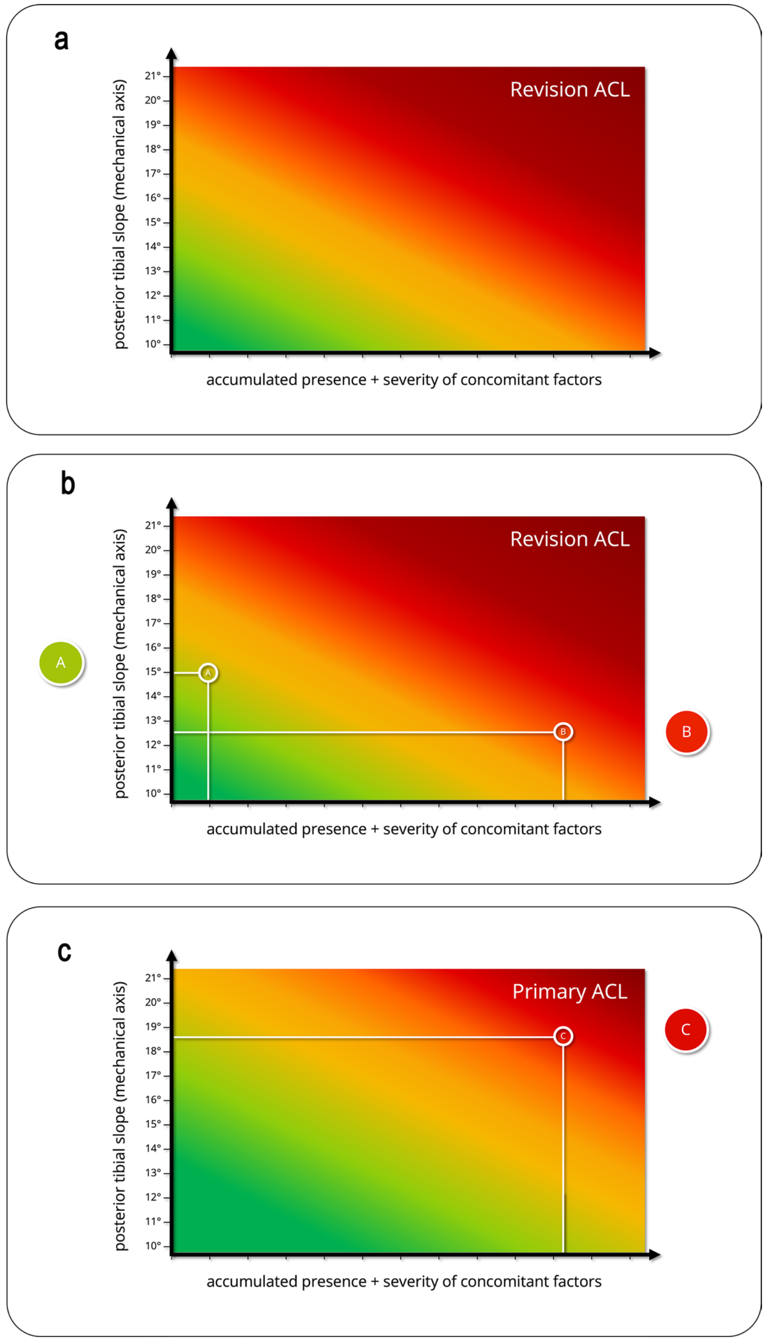

Fig. 3 Heat maps for the indication of a slope-decreasing osteotomy for the different settings of revision (a, b) and primary cases (c). Patient-specific factors are plotted on the x-axis, and the radiologically measured PTS on the y-axis. The point defined this way in this coordinate system defines the strength of the recommendation for slope decreasing osteotomy by its underlying color: Dark red indicates a strong recommendation for slope decreasing osteotomy whereas green means no recommendation for osteotomy (a). The white circles represent different exemplary possible patient conditions (b, c): Patient A has a high tibial slope of around 15° (MA) but has no further risk factors. The heat map shows "green". This patient might preferably be treated with ligament reconstruction only. Patient B has a moderately increased PTS of around 12.5° but has a number of severe concomitant factors, resulting in "red", and thus resulting in a strong recommendation for concomitant osteotomy. Patient C has a primary ACL injury (c). With a number of severe concomitant risk factors and a high PTS of 18.5° the heat map shows "dark orange", and ACL reconstruction combined with a slope changing osteotomy might be considered in this case

at this point that some additional factors for defining the indication of slope changing osteotomy have already been discussed [9, 10, 52, 53]. However, no approach has yet included the extensive range of risk factors, correlated them with the PTS and combined them into a comprehensive dynamic concept.

Figure 3 demonstrates the practical application: The presence and severity of individual conditions and risk factors listed in Table 1 should be analyzed and ultimately mapped to an increasing degree via the x-axis. This axis is intentionally not specified more precisely, as the individual significance of the respective factors cannot be reasonably stated and a scoring system based on available evidence is insufficient. However, many risk factors and increasing severity of those ultimately lead to a point far on the right on the x-axis. The tibial slope (ideally measured according to the mechanical axis) is plotted on the y-axis. The point defined this way in this coordinate system then defines the strength of the recommendation for an additional bony correction by the background color of the underlying heat map: from green (no recommendation for osteotomy) to dark red (strong recommendation for osteotomy). The authors recommend considering a slope-decreasing osteotomy in revision cases from a PTS ≥ 10° according to the mechanical axis and necessarily taking all factors of Table 1 into account.

Different heat maps for revisions and for the primary situation are proposed as slope changing osteotomy might also play a role in selected primary cases with high or excessive slope and severe additional risk [10]. It is important to the authors to clarify that this model and the used background colors should generally be understood as a path for complex decision-making rather than a model to clearly producing a yes or no answer. The result provides guidance and can then be used as a basis for what is ultimately a highly individual decision.

Limitations

The *Avalanche Concept* is a conceptual model that serves as a decision-making guide, but with current evidence it cannot and should not be used to provide an absolute decision. Future findings and results of clinical studies and future developments need to be integrated. However, the model can constantly be adapted by adjusting the color gradient of the heat map.

Further, the major focus of the concept is the ACL and the risk for further injury. However, in many cases of existing ACL insufficiency the dominant clinical problem is actually a different one, for instance secondary osteoarthritis or medial/lateral instability with varus or valgus deviation. In these even more complex cases, the PTS is also of exceptional importance, however, even more individualized treatment strategies are necessary then, which cannot be depicted in this model. Finally, it is essential to take into account the fundamental aspects of ACL reconstruction (anatomical reconstruction, meniscus therapy, additional stabilization, etc.) before considering the indication for a slope osteotomy.

Conclusion

The *Avalanche Concept* provides an individualized decision guidance for indicating slope decreasing osteotomies predominantly in revision ACL reconstructions by combining numerous individual and patient-specific factors with the measured PTS in a dynamic heat map model. Thus, it provides the basis for an individualized treatment decision.

Acknowledgements The authors have no funding to report.

Author contributions Philipp Schuster had the idea for this concept and this publication. The concept was developed in its details by all authors together. The specific factors and background information in the field of avalanche science were prepared by Philipp Schuster and Philipp Mayer. The first draft of the manuscript was written by Philipp Schuster and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data availability As a concept paper, this study does not contain any specific data.

Declarations

Conflict of interest Philipp Schuster received speaking fees and royalties from Newclip Technics (France). The other authors have no conflicts of interest do declare.

Ethics statement The concept and its publication have been approved by the institutional review board.

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References

1. Dean RS, Larson CM, Waterman BR (2021) Posterior tibial slope: understand bony morphology to protect knee cruciate ligament grafts. Arthroscopy 37:2029–2030. https://doi.org/10.1016/j.arthro.2021.05.006
2. Ni Q-K, Song G-Y, Zhang Z-J et al (2020) Steep posterior tibial slope and excessive anterior tibial translation are predictive risk factors of primary anterior cruciate ligament reconstruction failure: a case–control study with prospectively collected data. Am J Sports Med 48:2954–2961. https://doi.org/10.1177/0363546520949212
3. Salmon LJ, Heath E, Akrawi H et al (2018) 20-year outcomes of anterior cruciate ligament reconstruction with hamstring tendon autograft: the catastrophic effect of age and posterior tibial slope. Am J Sports Med 46:531–543. https://doi.org/10.1177/0363546517741497
4. Webb JM, Salmon LJ, Leclerc E et al (2013) Posterior tibial slope and further anterior cruciate ligament injuries in the anterior cruciate ligament-reconstructed patient. Am J Sports Med 41:2800–2804. https://doi.org/10.1177/0363546513503288
5. Dickschas J, Schubert I, Wagner M et al. Anterior Closed Wedge High Tibial Osteotomy for Slope Correction in Anterior Cruciate Ligament Insufficiency: A Preliminary Report of 100 Cases at a 2-Year Follow-up. Cartilage. 2025 Sep 15:19476035251364704. https://doi.org/10.1177/19476035251364704. Epub ahead of print. PMID: 40955063; PMCID: PMC12440914.
6. Dejour D, Saffarini M, Demey G, Baverel L (2015) Tibial slope correction combined with second revision ACL produces good knee stability and prevents graft rupture. Knee Surg Sports

Traumatol Arthrosc 23:2846–2852. https://doi.org/10.1007/s00167-015-3758-6
7. Rozinthe A, van Rooij F, Demey G et al (2022) Tibial slope correction combined with second revision ACLR grants good clinical outcomes and prevents graft rupture at 7-15-year follow-up. Knee Surg Sports Traumatol Arthrosc 30:2336–2341. https://doi.org/10.1007/s00167-021-06750-1
8. Sonnery-Cottet B, Mogos S, Thaunat M et al (2014) Proximal tibial anterior closing wedge osteotomy in repeat revision of anterior cruciate ligament reconstruction. Am J Sports Med 42:1873–1880. https://doi.org/10.1177/0363546514534938
9. Akoto R, Alm L, Drenck TC et al (2020) Slope-correction osteotomy with lateral extra-articular tenodesis and revision anterior cruciate ligament reconstruction is highly effective in treating high-grade anterior knee laxity. Am J Sports Med 48:3478–3485. https://doi.org/10.1177/0363546520966327
10. Song G-Y, Ni Q-K, Zheng T et al (2020) Slope-reducing tibial osteotomy combined with primary anterior cruciate ligament reconstruction produces improved knee stability in patients with steep posterior tibial slope, excessive anterior tibial subluxation in extension, and chronic meniscal posterior horn tears. Am J Sports Med 48:3486–3494. https://doi.org/10.1177/0363546520963083
11. Mabrouk A, Kley K, Jacquet C et al (2023) Outcomes of slope-reducing proximal tibial osteotomy combined with a third anterior cruciate ligament reconstruction procedure with a focus on return to impact sports. Am J Sports Med 51:3454–3463. https://doi.org/10.1177/03635465231203016
12. Beel W, Schuster P, Michalski S et al (2023) High prevalence of increased posterior tibial slope in ACL revision surgery demands a patient-specific approach. Knee Surg Sports Traumatol Arthrosc 31:2974–2982. https://doi.org/10.1007/s00167-023-07313-2
13. Schuster P, Mayer P, Schubert I et al (2024) Infratuberositary slope-decreasing anterior closed wedge proximal tibial osteotomy is safe and shows rapid bone healing. Knee Surg Sports Traumatol Arthrosc. https://doi.org/10.1002/ksa.12559
14. Condello V, Beaufilis P, Becker R et al (2023) Management of anterior cruciate ligament revision in adults: the 2022 ESSKA consensus: part II-surgical strategy. Knee Surg Sports Traumatol Arthrosc 31:4652–4661. https://doi.org/10.1007/s00167-023-07550-5
15. Gwinner C, Janosec M, Wierer G et al (2021) Graft survivorship after anterior cruciate ligament reconstruction based on tibial slope. Am J Sports Med 49:3802–3808. https://doi.org/10.1177/03635465211049234
16. Lee CC, Youm YS, Cho SD et al (2018) Does posterior tibial slope affect graft rupture following anterior cruciate ligament reconstruction? Arthroscopy 34:2152–2155. https://doi.org/10.1016/j.arthro.2018.01.058
17. Agneskirchner JD, Hurschler C, Stukenborg-Colsman C et al (2004) Effect of high tibial flexion osteotomy on cartilage pressure and joint kinematics: a biomechanical study in human cadaveric knees. Winner of the AGA-DonJoy Award 2004. Arch Orthop Trauma Surg 124:575–584. https://doi.org/10.1007/s00402-004-0728-8
18. Bernhardson AS, Aman ZS, Dornan GJ et al (2019) Tibial slope and its effect on force in anterior cruciate ligament grafts: anterior cruciate ligament force increases linearly as posterior tibial slope increases. Am J Sports Med 47:296–302. https://doi.org/10.1177/0363546518820302
19. Imhoff FB, Mehl J, Comer BJ et al (2019) Slope-reducing tibial osteotomy decreases ACL-graft forces and anterior tibial translation under axial load. Knee Surg Sports Traumatol Arthrosc 27:3381–3389. https://doi.org/10.1007/s00167-019-05360-2
20. Firth AD, Bryant DM, Litchfield R et al (2022) Predictors of graft failure in young active patients undergoing hamstring autograft anterior cruciate ligament reconstruction with or without a lateral extra-articular tenodesis: the stability experience. Am J Sports Med 50:384–395. https://doi.org/10.1177/03635465211061150
21. Mayer P, Hielscher L, Schuster P et al (2025) Evaluating the mechanical axis for detection of posterior tibial slope malalignment in ACL-deficient knees on lateral radiographs. Orthop J Sports Med 13:23259671241296856. https://doi.org/10.1177/23259671241296858
22. Hewett TE, Myer GD, Ford KR et al (2016) Mechanisms, prediction, and prevention of ACL injuries: cut risk with three sharpened and validated tools. J Orthop Res 34:1843–1855. https://doi.org/10.1002/jor.23414
23. Rahardja R, Zhu M, Love H et al (2020) Factors associated with revision following anterior cruciate ligament reconstruction: a systematic review of registry data. Knee 27:287–299. https://doi.org/10.1016/j.knee.2019.12.003
24. Shen X, Qin Y, Zuo J et al (2021) A systematic review of risk factors for anterior cruciate ligament reconstruction failure. Int J Sports Med 42:682–693. https://doi.org/10.1055/a-1393-6282
25. Zhao D, Pan J-K, Lin F-Z et al (2023) Risk factors for revision or rerupture after anterior cruciate ligament reconstruction: a systematic review and meta-analysis. Am J Sports Med 51:3053–3075. https://doi.org/10.1177/03635465221119787
26. Grassi A, Macchiarola L, Urrizola Barrientos F et al (2019) Steep posterior tibial slope, anterior tibial subluxation, deep posterior lateral femoral condyle, and meniscal deficiency are common findings in multiple anterior cruciate ligament failures: an MRI case–control study. Am J Sports Med 47:285–295. https://doi.org/10.1177/0363546518823544
27. Song G-Y, Zhang H, Zhang J et al (2018) Greater static anterior tibial subluxation of the lateral compartment after an acute anterior cruciate ligament injury is associated with an increased posterior tibial slope. Am J Sports Med 46:1617–1623. https://doi.org/10.1177/0363546518760580
28. Alm L, Krause M, Frosch K-H, Akoto R (2020) Preoperative medial knee instability is an underestimated risk factor for failure of revision ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 28:2458–2467. https://doi.org/10.1007/s00167-020-06133-y
29. Bernholt D, DePhillipo NN, Aman ZS et al (2021) Increased posterior tibial slope results in increased incidence of posterior lateral meniscal root tears in ACL reconstruction patients. Knee Surg Sports Traumatol Arthrosc 29:3883–3891. https://doi.org/10.1007/s00167-021-06456-4
30. Dzidzishvili L, Allende F, Allahabadi S et al (2024) Increased posterior tibial slope is associated with increased risk of meniscal root tears: a systematic review. Am J Sports Med. https://doi.org/10.1177/03635465231225981
31. Kodama Y, Furumatsu T, Tamura M et al (2023) Steep posterior slope of the medial tibial plateau and anterior cruciate ligament degeneration contribute to medial meniscus posterior root tears in young patients. Knee Surg Sports Traumatol Arthrosc 31:279–285. https://doi.org/10.1007/s00167-022-07095-z
32. Melugin HP, Brown JR, Hollenbeck JFM et al (2023) Increased posterior tibial slope increases force on the posterior medial meniscus root. Am J Sports Med 51:3197–3203. https://doi.org/10.1177/03635465231195841
33. Okazaki Y, Furumatsu T, Hiranaka T et al (2021) Steep posterior slope of the medial tibial plateau is associated with ramp lesions of the medial meniscus and a concomitant anterior cruciate ligament injury. Asia-Pac J Sports Med Arthrosc Rehabil Technol 24:23–28. https://doi.org/10.1016/j.asmart.2021.01.005
34. Keizer MNJ, Otten E (2019) Passive anterior tibia translation in anterior cruciate ligament-injured, anterior cruciate ligament-reconstructed and healthy knees: a systematic review.

Musculoskelet Surg 103:121–130. https://doi.org/10.1007/s12306-018-0572-6
35. Zhang Z, Shi W, Bai W et al (2023) Chronic ACL-injured patients show increased medial and global anterior tibial subluxation measured on 1-year postoperative MR images after primary single-bundle ACL reconstruction. J Orthop Surg Res 18:565. https://doi.org/10.1186/s13018-023-04028-5
36. Choi N-H, Lee D-M, Victoroff BN (2023) Bone morphological characteristics as risk factors for anterior cruciate ligament injury: comparison between contact and noncontact injury. Orthop J Sports Med 11:23259671231179757. https://doi.org/10.1177/23259671231179757
37. Ménétrey J, Duthon VB, Laumonier T, Fritschy D (2008) "Biological failure" of the anterior cruciate ligament graft. Knee Surg Sports Traumatol Arthrosc 16:224–231. https://doi.org/10.1007/s00167-007-0474-x
38. Mazy D, Cance N, Favroul C et al (2025) The impact of posterior tibial slope and static anterior tibial translation on ACL graft rupture rates after hamstring autograft reconstruction with lateral extra-articular tenodesis. Am J Sports Med 53:2379–2386. https://doi.org/10.1177/03635465251350397
39. Cronström A, Tengman E, Häger CK (2021) Risk factors for contra-lateral secondary anterior cruciate ligament injury: a systematic review with meta-analysis. Sports Med 51:1419–1438. https://doi.org/10.1007/s40279-020-01424-3
40. Schlumberger M, Schuster P, Schulz M et al (2017) Traumatic graft rupture after primary and revision anterior cruciate ligament reconstruction: retrospective analysis of incidence and risk factors in 2915 cases. Knee Surg Sports Traumatol Arthrosc 25:1535–1541. https://doi.org/10.1007/s00167-015-3699-0
41. Wiggins AJ, Grandhi RK, Schneider DK et al (2016) Risk of secondary injury in younger athletes after anterior cruciate ligament reconstruction: a systematic review and meta-analysis. Am J Sports Med 44:1861–1876. https://doi.org/10.1177/0363546515621554
42. Weiler A, Berndt R, Wagner M et al (2023) Tibial slope on conventional lateral radiographs in anterior cruciate ligament-injured and intact knees: mean value and outliers. Am J Sports Med 51:2285–2290. https://doi.org/10.1177/03635465231178292
43. Garra S, Li ZI, Triana J et al (2023) Posterior tibial slope in patients undergoing bilateral versus unilateral ACL reconstruction: MRI and radiographic analyses. Am J Sports Med 51:2275–2284. https://doi.org/10.1177/03635465231177086
44. Paschos NK, Reikersdorfer K, Jayne C et al (2024) Revision anterior cruciate ligament reconstruction in pediatric and adolescent patients yields low rates of graft failure and good functional scores, but low rates of return to sport: a systematic review. Arthroscopy S0749–8063(24):00612–00621. https://doi.org/10.1016/j.arthro.2024.08.014
45. Dejour H, Bonnin M (1994) Tibial translation after anterior cruciate ligament rupture. Two radiological tests compared. J Bone Jt Surg Br 76:745–749
46. Clinger BN, Plaster S, Passarelli T et al (2022) Differentiation in posterior tibial slope by sex, age, and race: a cadaveric study utilizing 3-dimensional computerized tomography. Am J Sports Med 50:2698–2704. https://doi.org/10.1177/03635465221108187
47. Chougule S, Tselentakis G, Stefan S, Stefanakis G (2015) Revision of failed anterior cruciate ligament reconstruction with quadrupled semitendinosus allograft: intermediate-term outcome. Eur J Orthop Surg Traumatol 25:515–523. https://doi.org/10.1007/s00590-014-1549-2
48. MARS Group, Wright RW, Huston LJ et al (2021) Association between graft choice and 6-year outcomes of revision anterior cruciate ligament reconstruction in the MARS cohort. Am J Sports Med 49:2589–2598. https://doi.org/10.1177/03635465211027170
49. Landrø M, Pfuhl G, Engeset R et al (2020) Avalanche decision-making frameworks: classification and description of underlying factors. Cold Reg Sci Technol 169:102903. https://doi.org/10.1016/j.coldregions.2019.102903
50. Munter W (1991) Neue Lawinenkunde: Ein Leitfaden fuer die Praxis. Schweizer Alpen-Club
51. Engler M, Mersch J, Schrag K (2001) SnowCard & Faktorencheck. Engler M
52. Dejour D, Rozinthe A, Demey G (2023) First revision ACL reconstruction combined with tibial deflexion osteotomy improves clinical scores at 2 to 7 years follow-up. Knee Surg Sports Traumatol Arthrosc 31:4467–4473. https://doi.org/10.1007/s00167-023-07493-x
53. Weiler A, Gwinner C, Wagner M et al (2022) Significant slope reduction in ACL deficiency can be achieved both by anterior closing-wedge and medial open-wedge high tibial osteotomies: early experiences in 76 cases. Knee Surg Sports Traumatol Arthrosc 30:1967–1975. https://doi.org/10.1007/s00167-022-06861-3

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