Measurement of the Posterior Tibial Slope using the Mechanical Axis on lateral X-rays is beneficial

Dissertation

zur Erlangung des akademischen Grades eines

Doktors der Medizin (Dr. med.)

an der

Medizinischen Fakultät der Universität Hamburg

vorgelegt von

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aus

Dortmund

2025

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Datum der mündlichen Prüfung: 08.09.2025

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Introduction

Knee Kinematics

Anatomy

The knee joint comprises four compartments: the medial and lateral tibiofemoral, the patellofemoral and the tibiofibular joint (Liu *et al.*, 2019; Mueller, 1982). Of these, the tibiofemoral joint is the most important joint as it transmits the body weight from the femur to the tibia during active walking. The knee is a gliding hinge joint, deemed as such by Hirschmann et al., allowing kinematic movements like gliding, rolling and rotating (Hirschmann and Müller, 2015).

Stabilizers

Ligaments like the anterior and posterior cruciate ligament, medial and lateral collateral ligament and the medial and lateral meniscus account as passive stabilizers providing balance in all ranges of motion, or more specifically giving static stability. Surrounding muscles, like the quadriceps femoris muscle, are active stabilizers providing the knee joint with dynamic stability (Hirschmann and Müller, 2015; Schipplein and Andriacchi, 1991).

Alignment in frontal plane

The alignment of the lower extremity can be radiographically assessed by reference to the mechanical and anatomical axis in a hip-to-ankle radiograph (Liu *et al.*, 2019). The mechanical axis, also known as the weight-bearing line, passes from the central femoral head to the midpoint of the tibiotalar joint. However, in neutral alignment, which refers to the mechanical axis passing through the centre of the knee, approximately 55 – 70% of the total knee load is transmitted to the medial compartment (Schipplein and Andriacchi, 1991). In cases of malalignment, the weight-bearing line cannot be maintained in its original position. The mechanical axis can pass the centre of the knee more medially, also known as varus malalignment, or laterally, named valgus malalignment. Depending on the existing misalignment there either is an increased load bearing on the medial or lateral compartment of the knee joint (Uquillas *et al.*, 2014). Consequently, the maldistribution of the weight during normal walking leads to further problems such as osteoarthritis (Amis, 2013; Oláh *et al.*, 2022).

Posterior Tibial Slope

Anatomical influence and radiological measurement

The sagittal alignment of the posterior tibial slope (PTS), or tibial slope (TS), contributes significantly to the antero-posterior stability of the knee (Dean, Larson and Waterman, 2021; Frank, 2004; Giffin *et al.*, 2004; Hashemi *et al.*, 2008; Hassebrock *et al.*, 2020). Many quantitative methodologies have been described to measure the PTS. Commonly, the PTS has been defined as the angle between an orthogonal line to an axis that is aligned in different ways on the tibial shaft and either the medial or lateral tibial plateau's dorsal inclination in sagittal plane (Agneskirchner *et al.*, 2004; Amis, 2013; Brazier *et al.*, 1996; Chiu, Zhang and Zhang, 2000; Hudek *et al.*, 2009; Wittenberg *et al.*, 2020) (Fig. 1). A positive angle indicates the inclination of the tibial plateau showing posteriorly, whereas a negative angle would show anteriorly (Matsuda *et al.*, 1999). The average angle depends on the used measurement method. The most popular method of PTS measurement utilizes a short lateral knee radiograph and two measurement points, one at 5cm and the second at 15cm below the joint line (the so-called proximal anatomical axis) and the diaphyseal axis as reference, a norm value of 10.0°±3.0° is described (Dejour and Bonnin, 1994). Faschingbauer et al. modified this method by using a full-length lateral tibial radiograph and setting different diaphyseal centre points. PTS values of 8.5°±3.2°, 9.8°±3.3° and 8.7°±3.1° with centre points at 6 and 16cm, 6 and 10cm and 16 and 20cm below the tibial plateau were outlined. When using the mechanical axis (MA) on a lateral radiograph of the whole tibia, angle values of 6.9°±3.3° were presented (Faschingbauer *et al.*, 2014). Yoo et al. compared the measurement of the PTS using five different axes on lateral radiographs of the whole limb and concluded various results ranging from 7.8° with the posterior cortical line up to 13.8° with the anterior cortical line (Yoo *et al.*, 2008). All these measurements focused on the medial plateau. However, differences between the medial and lateral tibial slope (representing either the medial or lateral tibial plateau) have also been described. Current literature presents controversial results concerning this matter. Ranging values for the tibial slope of the medial compartment of -3.0°-10.0° compared to 0.0°-10.0° for the lateral compartment, are described. Therefore, Hashemi et al. resulted in their MRI study that the lateral tibial slope, compared to the medial tibial slope, is steeper (Hashemi *et al.*, 2008). A CT-based study found similar results with an even wider range of values, whereas Haddad et al. did not find a significant difference between the medial and lateral compartment at all (Haddad *et al.*, 2012; Hashemi *et al.*, 2008; Nunley *et al.*, 2014). Hudek et al. compared the results for the medial and lateral plateau measurement between MRI and true lateral knee radiographs and detected an average difference of 3.4° (Hudek *et al.*, 2009).

The PTS is depending on other factors including ethnicity, as shown by many studies: A multi-centre study by Akçaalan et al. utilized 1800 lateral knee radiographs from five different countries and presented that the Turkish population has a steeper tibial slope, with a mean value of 10.6°±1.9°, compared to the mean values of Germany 8.5°±2.9°, Italy 5.4°±2.1°, United Kingdom 7.7°±2.7° and Spain 6.7°±3.2° (Akçaalan *et al.*, 2023). According to the research of Bisicchia et al. there is also a significant difference of PTS values between the black and white population, with the slope being steeper in black patients (Bisicchia *et al.*, 2017).

Figure 1 Full-length lateral tibial radiograph depicting the posterior tibial slope. Determination of the tibial slope based on the mechanical axis and medial tibial plateau's dorsal inclination on a radiograph of a patient presenting for anterior cruciate ligament reconstruction.

The PTS carries a significant impact on the stability of the knee joint and its biomechanics, especially regarding tibial translation (Chen *et al.*, 2022; Kumar and Gupta, 2022; Schatka *et al.*, 2018). A pre-existing anatomical variance as well as an iatrogenic change in the PTS, such during high tibial osteotomy (HTO), would lead to a shift of the sagittal line force between the femoral condyles and tibial plateau (Ahmad *et al.*, 2016; Agneskirchner *et al.*, 2004; Giffin *et al.*, 2004; Moon *et al.*, 2021). An increased TS would lead to a relocation of the femoral condyles posteriorly to the tibial plateau, which consequently would displace the force posteriorly leading to an enhanced femoral rollback. A cadaveric study of Giffin et al. showed that a steeper slope naturally leads to an anterior tibial translation in resting position with the highest being during knee extension and with a gradual decrease with flexion (Giffin *et al.*, 2004). A comparative study by Liu et al. emphasized this outcome by showing that a tibial slope of 12.0° presented with a 15.2mm tibial anterior displacement compared to 9.1mm with 4.0° (Liu and Maitland, 2003). Additionally, the shift led to a greater distance between the femoral condyles and tibial plateau and therefore increasing the pressure transfer onto the posterior tibial plateau and the strain exerting on the anterior cruciate ligament (ACL) (Beel *et al.*, 2023; Giffin *et al.*, 2004; Schuster *et al.*, 2018). A decreased PTS, on the other hand, would act vice versa.

Surgical importance

Due to the impeccable influence of the osseous alignment in the coronal and sagittal plane, maintaining the PTS gained significance during surgical procedures such as ligament reconstructive surgery, high tibial osteotomy and total knee arthroplasty (TKA) (Beel *et al.*, 2023; Bernhardson *et al.*, 2019a; Bernhardson *et al.*, 2019b; Bernhardson *et al.*, 2019c; Schuster *et al.*, 2018; Wittenberg *et al.*, 2020). In ligament reconstructive surgery, such as ACL and posterior cruciate ligament (PCL) reconstruction, it was allocated that the posterior tibial slope plays a crucial role. It was shown that the graft survival is significantly shorter with a steeper slope (most commonly defined as ≥12.0° measured with the proximal anatomical axis), causing up to 35% of the ACL grafts to fail and therefore significantly reducing its survival rate (Beel *et al.*, 2023; Christensen *et al.*, 2015; Salmon *et al.*, 2018; Webb *et al.*, 2013). Schuster et al. showed that when the tibial slope exceeds 12.5° there is a substantial risk for the ACL graft to fail after combined varus-correcting high tibial osteotomy and anterior cruciate ligament reconstruction (ACL-R) (Schuster *et al.*, 2018). Webb et al. also described an increased risk by a factor of 5 for further ACL graft injury after reconstruction with a slope of ≥12.0° (Webb *et al.*, 2013). An increased rupture rate was also seen when it comes to primary PCL ruptures and a concurrent decreased TS due to increased forces exerting on the PCL. A steeper slope however was shown to be protective (Bernhardson *et al.*, 2019a; Bernhardson *et al.*, 2019c; Dean, Larson and Waterman, 2021). Therefore, it is of utmost importance to address the PTS in ligament reconstructive surgery, especially before revision reconstruction, and to consider correction osteotomies of the TS (Beel *et al.*, 2023; Dejour *et al.*, 2015; Winkler *et al.*, 2021). A meta-analysis by Nha et al. emphasised, that surgical interventions such as open-wedge and closed-wedge HTO in order to correct frontal malalignment can also influence the PTS. More precisely, they can have a negative effect on the knee biomechanics (Nha *et al.*, 2016). Furthermore, both, a steeper and narrower PTS, can have a negative impact on knee protheses, according to Wittenberg et al.. Increased wear and tear on the polyethylene material of the prothesis and following aseptic loosening can be caused by a steep slope, whereas a flat PTS can lead to sinkage of the tibial inlay due to increased pressure transmitted onto the anterior aspect of the tibial head (Matsuda *et al.*, 1999; WASIELEWSKI *et al.*, 1994; Wittenberg *et al.*, 2020).

Measurement options

Given the clinical importance of the PTS, it is crucial to have a reliable and exact measurement option available. As mentioned above, different methods have been reported in literature, most of them using a tangential line along the medial tibial plateau, since it is easily reproduceable on lateral radiographs, but different axes (de Boer *et al.*, 2009). The different methods described are the mechanical axis (MA), anterior tibial cortex (ATC), proximal anatomical axis (PAA), anatomical axis (AA), posterior tibial cortex (PTC), fibular proximal anatomical axis (FPAA) and fibular shaft axis (FSA), with the most important being the MA, PAA and AA (Beel *et al.*, 2023; Brazier *et al.*, 1996; Lipps *et al.*, 2012; Utzschneider *et al.*, 2011; Wittenberg *et al.*, 2020). In daily clinical routine a radiograph is a standard imaging method. For TS measurement this can either be a standard lateral knee radiograph or full-length lateral knee radiograph, which in comparison includes the upper ankle joint (Beel *et al.*, 2023; Dean, Larson and Waterman, 2021; Faschingbauer, 2021; Faschingbauer *et al.*, 2014; Gwinner *et al.*, 2019; Utzschneider *et al.*, 2011; Wittenberg *et al.*, 2020). Commonly the PAA is used on standard and the AA and MA on full-length lateral tibial radiographs as a reference line (Dean *et al.*, 2021; Faschingbauer *et al.*, 2014; Hees, Zielke and Petersen, 2023). Since a short lateral x-ray does not need as much technical requests, is less time consuming and has less radiation exposure compared to a lateral radiograph of the whole lateral tibia, the PAA is more commonly used as a measurement method in daily clinical routine. Hence, for the PAA several studies have described a cut-off value of >12.0°, however those have been controversially discussed by other studies (Salmon *et al.*, 2018). Those either suggested a lower threshold, whereas others questioned the anatomical influence of an increased PTS as a whole (Dæhlin *et al.*, 2022; de Sousa Filho *et al.*, 2021; Fares *et al.*, 2023; Hinz *et al.*, 2023; Lee *et al.*, 2018; Mandalia *et al.*, 2023; Salmon *et al.*, 2018). Generally, one should be cautious to define a real threshold, as it has been shown that there is not a single value with massively increased risk, but more a nearly linear correlation between slope and ACL graft rupture (Firth *et al.*, 2022). When measuring the PTS with the MA no cut-off values have yet been described. When comparing the results between PAA and MA measurements of previous studies a mean difference of 1.2° was found (Dean *et al.*, 2021; Faschingbauer *et al.*, 2014; Hees, Zielke and Petersen, 2023; Yoo *et al.*, 2008).

Dean et al. compared the two radiographic options, standard to full-length lateral tibial radiograph, and found no significant difference when measuring the PTS with the PAA. Therefore they concluded that a standard lateral knee radiograph is an accurate measurement option (Dean *et al.*, 2021). Faschingbauer et al. however hypothesised that a full-length lateral knee radiograph is needed to fully be able to analyse and measure the PTS. Their study showed that there will be an overestimation by 3.0° when only taking a standard lateral knee radiograph. Therefore, reasoning that the less of the lower limb is outlined, the overestimated the measurement will be and hence recommend to a least depict 20cm of the tibia to allow closes estimation (Faschingbauer, 2021; Faschingbauer *et al.*, 2014).

Another research study emphasises the before mentioned outcome by presenting underestimated slope results with an increased anterior tibial bowing in the diaphysis and only using standard imaging for measurement (Hees, Zielke and Petersen, 2023).

Hashemi et al., however, criticised that a radiograph is a two-dimensional (2D) imaging module, but the knee joint itself a three-dimensional (3D) object and therefore recommend using a 3D imaging modality, like CT and MRI, for a more precise analysis of the medial and lateral TS (Hashemi *et al.*, 2008). It was argued that a falsified outcome with a 2D modality can already occur with a minor malrotation of the tibial shaft and an inaccuracy while measuring is due to an image morphological overlap of the medial and lateral slope and hence more difficult to identify (Haddad *et al.*, 2012; Hudek *et al.*, 2009; Lipps *et al.*, 2012; Utzschneider *et al.*, 2011). Due to the possible mitigation of measuring errors occurring with malrotation, CT and MRI are more accurate (Gwinner *et al.*, 2019).

Nevertheless, it is said that 3D imaging modalities are more expensive, time consuming, have limited availability, do not show the whole tibia, need specialised software systems and do not count to a standard day to day imagine method in clinical routine (Hudek *et al.*, 2009). Therefore, a full-length lateral knee radiograph is a sufficient and less time-consuming alternative (Akamatsu *et al.*, 2016; Gwinner *et al.*, 2019). But to date there is still debate on how to measure the PTS on a radiograph, and no distinct quality criteria for lateral tibial radiographs have yet been described in terms of optimal slope measurement. So, for this study it was hypothesized that when measuring the PTS with the PAA on a standard lateral knee radiograph pathological slope values will be missed due to a malformation of the distal tibia which can be detected with a long x-ray and using the mechanical axis.

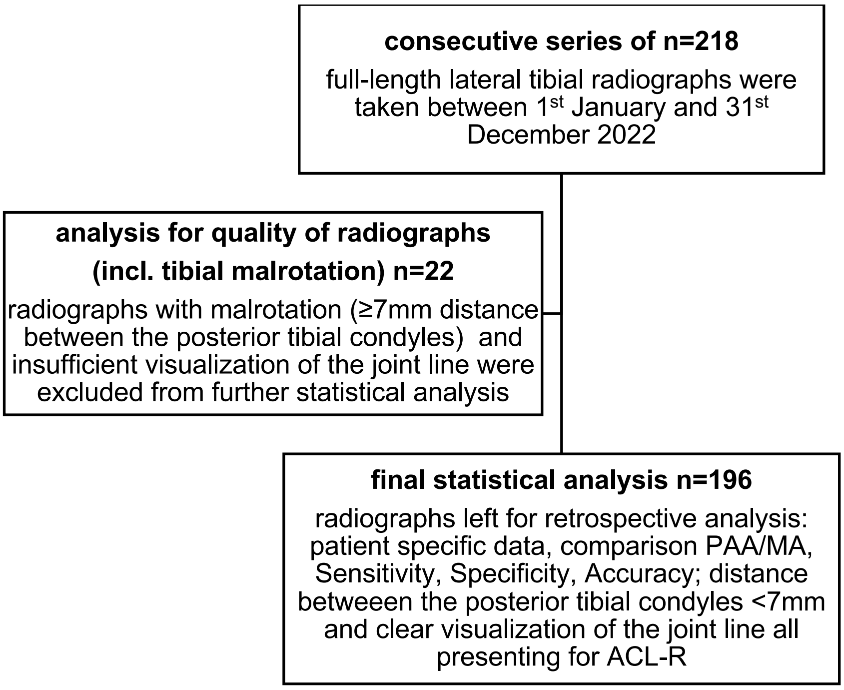
Materials and Methods

The clinical study protocol was approved by the local research ethics board (Ethikkommission of the Landesärztekammer Baden-Württemberg, Germany, F-2014-022).

Clinical Trial Arrangements

With the help of a patient collective of the Orthopaedic Hospital Markgroeningen in Germany 218 full-length lateral tibial radiographs, taken in a standing position with a straight lateral beam path, were retrospectively reviewed. The patients presented for revision anterior cruciate ligament reconstruction in 2022 and were mainly a Caucasian, middle European collective. The lateral radiographs were first analysed for malrotation, as previous studies emphasized that tibial alignment plays a huge role regarding PTS measurement (Kessler *et al.*, 2003; Weinberg *et al.*, 2017). If the distance between the posterior medial and lateral tibial condyles, measured in millimetres, was ≥7mm those were excluded, since initial analysis presented with increased inaccurate measurement between the two methods (PAA and MA). Radiographs were also excluded if no clear joint line or well positioned medial and lateral tibial plateaus were depicted. From the 218 radiographs, 196 were left for the final statistical analysis since 22 were excluded after not meeting the above-mentioned criteria (Fig. 2). Table 1 displays an overview of patient characteristics.

Figure 2 Flowchart radiograph selection



PAA: proximal anatomical axis

MA: mechanical axis

ACL-R: anterior cruciate ligament reconstruction

(Figure taken from: (Mayer *et al.*, 2025))

Table 1 Demographics

Number of cases	196
Sex	
Female	59 (30.1)
Male	137 (69.9)
Age (years)	37.1 ± 12.2 (14 – 66)

(Figure taken from: (Mayer *et al.*, 2025))

All x-rays were merged from two automatically taken images to prevent projection errors due to ray deflection. One beam focused on to the tibiotalar joint and the other focused on to the lower third of the tibia. All x-rays were taken with a 25mm reference sphere. A line connecting the centre of the medial tibial plateau and the centre of the tibiotalar joint in sagittal plane is referred to the MA (Yoo *et al.*, 2008). The PTS depicts an angle between an orthogonal line to the MA and a tangential line to the medial tibial plateau. Yoo et al. describe a line connecting the midpoint 5 and 15cm below the joint line as the PAA (Yoo *et al.*, 2008). Here the PTS describes an angle between an orthogonal line to the PAA and a tangential line to the medial tibial plateau. For the radiographic measurements a circle tool was used to identify the midpoints of the medial tibial plateau, tibial shaft and plafond. The midpoints were set by default by the tool. The distance (in mm) measured between the most posterior aspect of the medial and lateral tibial condyle, referred to as tibial overlapping (Fig. 3).

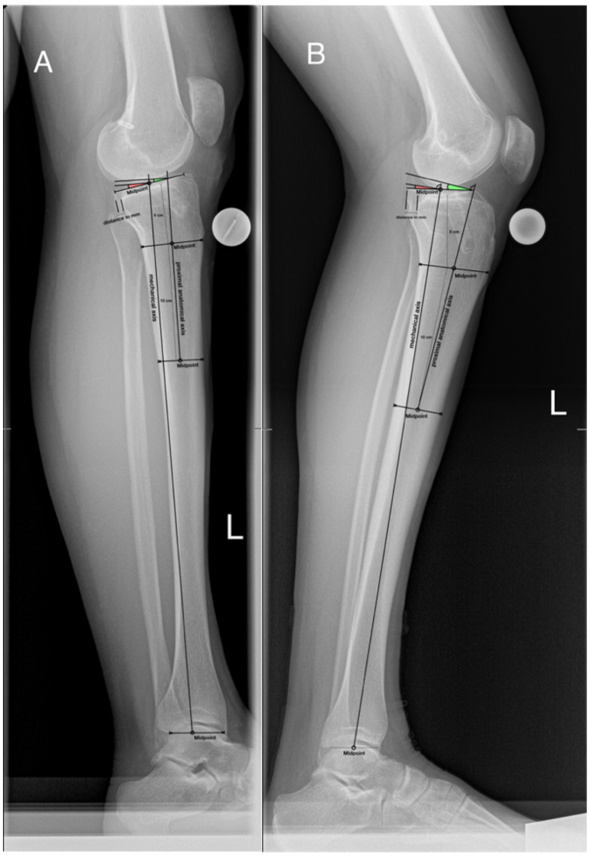


Figure 3 Lateral tibial radiographs and its different posterior tibial slope measurement options
The red angles depict the mechanical axis whereas the green angles show the measurement of the posterior tibial slope using the proximal anatomical axis. Radiographs with a correct rotation of the posterior tibial condyles with a difference of <7mm (A) and an increased internal rotation with ≥7mm between the posterior tibial condyles (B) are seen.

(Figure taken from: (Mayer *et al.*, 2025))

The radiographs analysis was performed with a PACS system (Xero Viewer, Agfa Health care N.V., Mortsel, Belgium) and was done twice by two trained orthopaedic surgeons, to valuate inter-observer reliability, with at least six weeks apart. Preceding measurements were masked. The obtained data was analysed based on the different analytic approaches and the resulting differences in PTS configuration.

Data was analysed retrospectively. Statistical analysis was then conducted utilizing IBM SPSS Statistics for Windows. The statistical evaluation for parametric clinical data was done with the two tailed t-test. The intraclass correlation coefficient (ICC) calculated the intra- and inter-observer reliability for the differences between the PTS measurement with the PAA and MA. The trustworthiness was defined poor (<0.50), moderate (0.50≤ICC<0.75), good (0.75≤ICC<0.90) or excellent (≥ 0.90), as per the ICC. To statistically compare the measurement techniques a linear correlation (Pearson correlation) was used.

Radiographic measurements of the PAA and MA were compared. So far, no standard values or thresholds have been defined for the mechanical axis. Therefore, the sensitivity and specificity of measurement of the proximal anatomical axis to detect a pathological mechanical axis have been examined for different defined thresholds of the mechanical axis. A PTS with PAA values ≥12.0° were defined as pathological, since many previous studies presented an increased risk for ACL graft insufficiency or graft re-rupture with a higher threshold (Lee *et al.*, 2018; Mandalia *et al.*, 2023; Salmon *et al.*, 2018). No pathological cut-off value for the MA have been defined. Therefore, four groups were categorized with defined potential pathological threshold values for the MA: Group 1: PTS with MA ≥10.0° and PAA <12.0°; Group 2: PTS with MA ≥10.5° and PAA <12.0°; Group 3: PTS with MA ≥11.0° and PAA <12.0°; Group 4: PTS with MA ≥11.5° and PAA <12.0°. Further, to analyze a pathological PTS (≥12.0°) for every subgroup sensitivity, specificity, and accuracy of the PAA was assessed and matched, as standard, to the varies cut-off values of the MA. Descriptive results are presented as mean ± standard deviation (and range), if not denoted alternatively.

Results

A significantly larger difference for PTS measurement between the PAA and MA was seen when comparing the two groups with an overlapping of the posterior tibial condyles of ≥7mm compared to <7mm ($p < 0.001$). A posterior condylar overlap of ≥7mm showed increased inconsistent results, with the difference between PAA and MA being 1.9° ± 1.4° (n = 22). Whereas in the group with a <7mm overlap of the posterior tibial condyles the mean difference was 1.1° ± 1.2° (n = 196). The median PTS difference in this group was 1.1°, with 25% surpassing 2° with a peak of 4.1°. A median value of 1.9° was estimated when the distance measured ≥7mm, whereof 50% surpassed 2° with a maximum of 5.1°. Hence, radiographs with a posterior tibial overlap of ≥7mm were excluded from further analysis.

Radiographic measurement results are depicted in Table 2. When comparing the results of PTS a mean difference of 1.1° ± 1.2° (-2.4° to 4.1°) was seen between the MA and PAA, with no significant difference of the slope between men and women identified (women vs men MA $p = 0.560$; women vs men PAA $p = 0.393$). PTS measurement with the PAA in

16% of the cases (N = 32) showed smaller values than when measured with the MA. A slope range between 9.0° to 14.0° was seen in 56% of the 32 cases (n = 18).

Table 2 Mean Tibial Slope

	Total n = 196	Women n = 61	Men n = 135
MA	9.4° ± 3.8°	9.7° ± 3.5°	9.3° ± 3.9°
	(0.4° to 21.9°)	(0.8° to 17.9°)	(0.4° to 20.9°)
PAA	10.5° ± 3.5°	10.8° ± 3.2°	10.3° ± 3.8°
	(1.7° to 20.9°)	(1.7° to 17.5°)	(3.1° to 20.7°)
Difference PAA – MA	1.1° ± 1.2°	1.1° ± 1.0°	1.0° ± 1.2°
	(-2.4° to 4.1°)	(-0.7° to 4.1°)	(-2.4° to 4°)

MA: mechanical axis

PAA: proximal anatomical axis

Women vs men MA p = 0.56; women vs. men PAA p = 0.39

A strong linear correlation was found between the MA and PAA (Pearson r = 0.95). The difference between MA and PAA showed a simultaneous trend to decline with rising PTS values measured with the MA. When using the ICC for PTS measurement with the MA an excellent intra- and inter-observer reliability of 0.97 (95% CI [0.96; 0.98]) and 0.95 (95% CI [0.93; 0.96]), respectively, were detected. Also, with the PAA for PTS measurement, when using the ICC, an excellent intra- and inter-observer reliability of 0.96 (95% CI [0.95; 0.97]) and 0.91 (95% CI [0.88; 0.93]), respectively, were found. Sensitivity, specificity and accuracy using PAA for the different thresholds of the MA are displayed in Table 3.

Table 3 Sensitivity, specificity and accuracy for identification of pathological PTS values using the PAA vs. MA for the different subgroups

	Sensitivity	Specificity	Accuracy
Group 1 (MA ≥ 10.0°; PAA < 12.0°)	73%	98%	86%
Group 1 (MA ≥ 10.5°; PAA < 12.0°)	84%	97%	92%
Group 1 (MA ≥ 11.0°; PAA < 12.0°)	87%	93%	91%
Group 1 (MA ≥ 11.5°; PAA < 12.0°)	95%	89%	91%

MA: mechanical axis

PAA: proximal anatomical axis

Discussion

The fundamental finding of this study regarding a reliable screening of a pathological PTS was that measuring using the MA is advantageous to the PAA, as PAA fails to identify distal alignment changes in sagittal plane and hence leading to increased PTS results.

In several studies the outcome for determining pathological PTS values on a standard lateral knee radiograph compared to a full-length lateral tibial radiograph have been shown to be inferior (Faschingbauer *et al.*, 2014; Hees, Zielke and Petersen, 2023). Hees et al. showed that especially with a malalignment of the lower tibia the results can be falsified and can even lead to an underestimation of the slope measurement (Hees, Zielke and Petersen, 2023). Further, with a lateral radiograph of the whole tibia, and using the MA for PTS measurement, a correlation was seen relating anterior tibial bowing (Hees, Zielke and Petersen, 2023). The present study emphasized the theory of the PAA not accurately representing the tibial load bearing by presenting that PTS measurement with the MA, compared to with the PAA, resulted in higher PTS values in 16%. This result is thought to be indicative of an existing anterior tibial bowing. Even though the anterior tibial bowing in the current study was only interpreted in a geometrical analysis, and not explicitly measured, it is known that in a lateral tibial radiograph the PAAs angulation will be more dorsally inclined. Respectively, the PTS will decrease whereas the reference to the medial tibial plateau will be unchanged. This osseous variation however does not influence measurement with the MA. It was noted that TS values measured with the MA are comparatively smaller to the PAA values. A tendency of approach of the values, however, was seen in the present study between the two methods, which underlines the fact that the MA is not affected by beforementioned osseous variations. A comparable difference between the reference axis was published by Dean et al. (Dean *et al.*, 2021). They used the PAA, MA and AA on full-length lateral tibial radiographs as reference for PTS analysis. Here a difference of >2.0° in 21% was discovered regarding the PTS values, comparing the PAA and AA, just as, when comparing PAA and MA as reference, in 55% a difference of ≥2.0° was detected. This study outcome emphasizes the present studies data. Mechanical loading conditions in sagittal plane cannot accurately be predicted by the PAA as a reference for measurement of pathological PTS values. Assessment is thereby by the authors recommended to be done on a full-length lateral tibial radiograph using the MAA for measurement.

In the current literature a threshold level for the PAA of >12.0° has been described when talking about an increased risk after ACL-R failure (Beel *et al.*, 2023; Gwinner *et al.*, 2021; Salmon *et al.*, 2018; Webb *et al.*, 2013). However, to the authors best knowledge no cut-off value for the MA, in relation to increased ACL-R failure, has yet been defined. Varies publications present a mean difference of 1.2° (median 1.1°) with a range of 0.2° - 2.3° when analysing the discrepancy between PAA and MA for PTS values (Dean *et al.*, 2021;

Faschingbauer *et al.*, 2014; Hees, Zielke and Petersen, 2023; Yoo *et al.*, 2008). It could be assumed that there might also be a pathological influence regarding the TS in a corresponding value range when measuring with the MA. Hence, in the current study subgroups were designed to cover the range of PTS values from 10.0° to 11.5° measured with the MA as reference. With the given data presented in this study however no clear cut-off value could be defined but a pathological range for slope measurement with MA of 10.5° to 11.0° was suspected. With a presumed pathological PTS defined as MA of 10.5° or 11.0°, a slope of <12.0° was measured with PAA in 16% and 13%, respectively, and these cases would have been missed. Still 5% of the patients would have presented with a slope measured with the PAA of <12.0° with a presumed value of 11.5° with MA. The result would indicate that the patients screening for pathological TS with MA present with discernibly steeper PTS values whilst being overlooked with PAA. This difference, additionally, emphasises the before mentioned assumption of PAA missing out in distal tibial malalignment and the unreliability to represent relevant mechanical loading conditions of the tibia in sagittal view.

Recent studies reported a strong correlation between a steep slope and an increased ACL-R failure and graft insufficiency (Beel *et al.*, 2023; Bernhardson *et al.*, 2019b; de Sousa Filho *et al.*, 2021; Dean, Larson and Waterman, 2021) It is not yet clear at what extended a slope correction osteotomy is indicated. Though especially concerning correction osteotomies mechanical loading conditions are critical and for planning slope reducing osteotomies the accuracy of PTS measurement is crucial. When comparing the measurement results of the current study between the PAA and MA for PTS screening several patients could not be determined correctly when only using the PAA. Presuming a PTS with the MA of 10.5° to 11.0° and interpreting the PAA as an analytical technique, a sensitivity of 84% or 87% indicates the insufficiency. However, the other way round, of the presented collective 3 patients showed a slope of >12.0° measured with the PAA, whilst with the MA a PTS of below 10.5° was identified. This implies that these patients, according to the mechanical analysis, might have a non-critical PTS, while presenting a pathological value with the proximal anatomical analysis. This could further cause overtreatment as a result of overestimation. In the current study group, it was seen that while the PTS was <9.0° measured with the PAA, with the MA no PTS of >10.5° was identified. Also, when exceeding 14.0° with the PAA, no slope of <10.5° was measured with the MA. According to this finding of the present study a save interpretation zone, when using the PAA for PTS measurement, below 9.0° and above 14.0° could be determined. In the range between 9.0° and 14.0° one must be cautious when wanting to identify a pathological PTS with the PAA as it is not a save indicator. The MA presented with higher PTS values in 32 cases (16%) as to the PAA, as mentioned above. This was detected in 56% of these cases (n=18) when the slope was between 9.0° and 14.0° measured with the PAA. This again strongly represents the inefficient representation of the mechanical loading conditions by the PAA in sagittal plane, especially with PTS values between 9.0° to 14.0°. When analysing the alignment in frontal plane the MA already is the gold standard. Deformity analysis in sagittal plane for PTS measurement should be done using the MA as reference, too to decrease the risk of under- or overcorrection due to under- or overestimation. Hence, pre-operative assessment on the mechanical analysis in sagittal plane is strongly advised to be performed on full-length lateral tibial radiograph using the MA as reference as it allows a more tailored approach.

The current study detected another riveting outcome namely that an overlapping of the tibial condyles of ≥7mm presented with an increased discrepancy between the measurement values of the PTS in reference to the PAA and MA. Utzschneider et al. already reported that tibial rotation has a high influence on the radiographically acquired PTS values by presenting high variances between the measured outcome (Utzschneider *et al.*, 2011). A study by Gwinner et al. presented measurements results on images referring to femoral condylar overlap. It reported a measurement difference of the PTS by both raters by 2.0° with an overlapping of ≥5mm (Gwinner *et al.*, 2019). Rotational malalignment is associated with increased PTS, as reported in previous studies by Kessler et al. and Weinberg et al., because of radial beam changes on the x-ray (Kessler *et al.*, 2003; Weinberg *et al.*, 2017). Rotational alignment, according to Weinberg et al., is recommended to be controlled using the posterior tibial condyles as an anatomic landmark, to which the authors of the present study can only agree with (Weinberg *et al.*, 2017). Therefore, when identifying the slope on lateral tibial radiographs it seems more fitting, as a criterion of quality, to measure the posterior tibial condyles.

Limitations

There are several limitations of this study that must be considered. First, it must be kept in mind that this study was done with a Caucasian, middle European ethnical population. As shown in the available research, it plays a significant role, as wide ranges concerning PTS values between ethnic groups are recorded (Bisicchia *et al.*, 2017; Chen *et al.*, 2022; Fan *et al.*, 2017; Faschingbauer, 2021; Han *et al.*, 2016; Kacmaz *et al.*, 2020). Additionally, it must be taken into account that our cohort was selected upon their medical background, which had to include graft failure after ACL-R. Hence, they were more likely to show a pathological PTS, than a group without a previous ACL injury. For this reason, the mean values stated in this study cannot be taken routinely as standard values.

Article

Original Research

Evaluating the Mechanical Axis for Detection of Posterior Tibial Slope Malalignment in ACL-Deficient Knees on Lateral Radiographs

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Background: Distal tibial deformities are not assessed using the proximal anatomical axis (PAA) to determine the posterior tibial slope (PTS). Therefore, it seems advantageous to measure PTS on full-length lateral tibial radiographs using the mechanical axis (MA).

Purposes: To (1) compare the PTS measurements using the MA and the PAA and (2) determine whether using the PAA fails to detect a certain number of significantly elevated PTS values compared with using the MA.

Study Design: Cohort study (Diagnosis); Level of evidence, 3.

Methods: Full-length lateral tibial radiographs of 218 consecutive cases were reviewed. Radiographs were checked for malrotation. Therefore, the distance between the posterior tibial condyles was measured in millimeters. Patients with a difference of ≥7 mm between the posterior tibial condyles were excluded, leaving 196 cases for the final statistical analysis. The PTS was measured using the MA and the PAA. Differences between these 2 techniques were analyzed. The sensitivity and specificity of the PAA as a screening method for pathological PTS were calculated, with the MA as the standard for comparison. Four subgroups were formed, all with PAA <12° and different lower limits for the MA: group 1, MA ≥10°; group 2, MA ≥10.5°; group 3, MA ≥11°; and group 4, MA ≥11.5°.

Results: Radiographs with ≥7 mm between the posterior tibial condyles showed an increased inconsistency between the PTS measurement with the MA and the PAA. In the group with a distance of <7 mm between the posterior tibial condyles (n = 196), the mean PTS measured with the MA was 9.4° ± 3.8° (range, 0.4° to 21.9°), and the mean PTS was 10.5° ± 3.5° (range, 1.7° to 20.9°) according to the PAA. The mean difference in PTS between the PAA and the MA was 1.1° ± 1.2° (range, –2.4° to 4.1°; *P* < .001). Group 1 had a sensitivity of 73% and specificity of 98%; group 2, sensitivity of 84% and specificity of 97%; group 3, sensitivity of 87% and specificity of 93%; and group 4, sensitivity of 95% and specificity of 89%.

Conclusion: Measuring the PTS using the MA was advantageous, as the measurement with the PAA did not correctly identify all cases with sagittal alignment changes. The proportion of patients with pathologically increased PTS not identified with the proximal anatomical measurement, reflected by the sensitivity, depended on the threshold value defined for the MA. Lateral radiographs, showing an increased distance between the posterior tibial condyles, indicated malrotation of the tibia leading to measurement inaccuracy.

Keywords: anterior cruciate ligament; knee, mechanical axis; osteotomy; posterior tibial slope; proximal anatomical axis

Bony malalignment is an important factor influencing the outcome of ligament reconstruction surgery around the knee.[26] The alignment in the sagittal plane has recently gained substantial interest. The posterior tibial slope (PTS) was proven to play a key role in ligament reconstructive surgeries, such as anterior cruciate ligament (ACL) and posterior cruciate ligament reconstruction.[2,3,7,23,25,28] PTS abnormalities were shown to result in detrimental biomechanical changes.[12,24]

The Orthopaedic Journal of Sports Medicine, 13(1), 23259671241296858
DOI: 10.1177/23259671241296858

The PTS describes the angulation of the tibiofemoral joint line in the sagittal plane. Technically, the PTS is defined as the angle between the tibial plateau (joint line) and the sagittal shaft axis of the tibia. Different methods to measure the PTS have been described. These different methods all use a line tangential to the medial tibial plateau as a reference. However, different shaft axes are used to calculate the PTS. The most common techniques involve using the proximal anatomical axis (PAA), anatomical axis (AA), or the mechanical axis (MA) of the tibia.[11,27,30]

In patients undergoing ACL reconstruction (ACLR), an increased PTS is associated with higher rates of ACL graft deficiency and ACL graft retears.[14,20,23,28] For the PAA, a cutoff of 12° for the PTS has been published in several previous studies, describing values exceeding this threshold as a risk factor.[19,21,23] These findings were discussed controversially by other publications. Some suggested even lower threshold values,[8,10] while others questioned the role of increased PTS values as a relevant risk factor.[6,16] For the PTS measurement using the MA, no cutoff values have been described. There is a mean difference of 1.2° when comparing the mean difference of the PTS between the MA and the PAA from several previously published studies.[9,11,15,30] The measurement with the PAA is widely used, as this method can be measured on short lateral radiographs in daily clinical routine. In comparison, the technique to measure the MA has greater technical requirements, as the whole lateral tibia must be captured on the lateral radiograph, making this technique less available and more time-consuming. An advantage of the MA is the possibility to evaluate the overall alignment of the tibia in the sagittal plane so that a distal malalignment can also be detected.

In daily clinical routine, an exact and reliable measurement of the PTS is crucial for managing cases of ACL deficiency and planning osteotomies for PTS correction. The intra- and interrater agreement for the different methods is high.[30] Measuring the PTS using a long tibial axis, however, has resulted in systematic differences when compared with measurements using a proximal tibial axis.[9,11,15] Most values and thresholds reported in the literature are generally based on the PAA. It seems, however, reasonable to use the MA to estimate the mechanical loading conditions, analogous to the use of the MA in the frontal plane.

Therefore, the purposes of this study were to (1) compare the measurement of the PTS using the MA and the PAA and (2) determine whether using the PAA fails to detect a certain number of significantly elevated PTS values compared with using the MA. We hypothesized that measuring the PTS using the PAA would not identify all cases with distally induced sagittal alignment changes resulting in noticeably increased PTS compared with measuring the MA.

METHODS

Data Selection

A series of 218 consecutive full-length lateral tibial radiographs were taken between January 1, 2022, and December 31, 2022. These radiographs were taken primarily from a Caucasian, Central European population. As malrotation of the tibia has been described to have a major impact on PTS measurement,[18,29] the lateral radiographs were checked for rotational alignment. In the first analysis, the tibial overlapping was measured as the distance (in mm) between the most posterior aspect of the medial tibial condyle and the most posterior aspect of the lateral tibial condyle (Figure 2). It was hypothesized that a difference of $\geq$7 mm between the posterior tibial condyles would result in measurement inaccuracy. Excluded were radiographs without clear visualization of the joint line or without well-aligned medial and lateral tibial plateau, indicated by the sclerotic lines. After excluding radiographs not meeting the criteria described from further statistical analysis, data from 196 radiographs were left for retrospective comparison of the PTS measured either with the PAA or the MA. All patients who were included presented for ACLR. The radiograph selection process is displayed in Figure 1.

Ethical approval was given by the local institutional review board (No. 03-2023).

Radiographic Measurement

Radiographs were taken with patients in a standing position, with a straight lateral beam path. Two x-rays were automatically captured to avoid projection errors due to beam divergence: one x-ray with the central ray centered on the tibial joint line, and another x-ray centered on the distal third of the tibia. The radiographs were then automatically stitched together to display the full length of the

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Final revision submitted July 19, 2024; accepted July 30, 2024.

The authors declared that they have no conflicts of interest in the authorship and publication of this contribution. AOSSM checks author disclosures against the Open Payments Database (OPD). AOSSM has not conducted an independent investigation on the OPD and disclaims any liability or responsibility relating thereto.

Ethical approval for this study was obtained from Orthopedic Hospital Markgroeningen (2023_03).

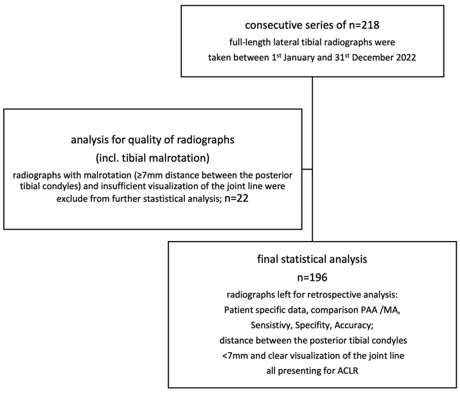

Figure 1. Flowchart of patient selection. ACLR, anterior cruciate ligament reconstruction; incl., including; MA, mechanical axis; PAA, proximal anatomical axis.

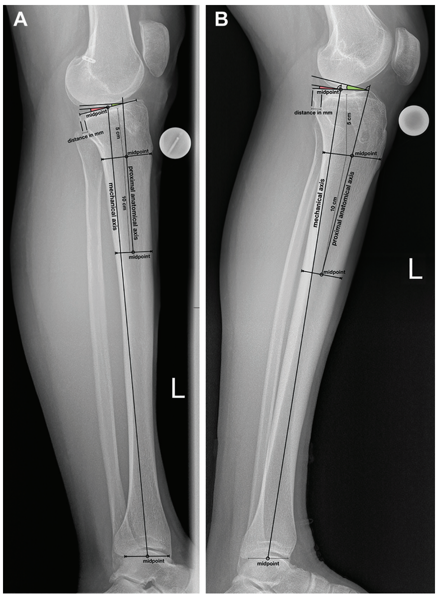

Figure 2. Different methods for measuring the PTS on a lateral radiograph: red angle, measurement of the PTS using the MA; green angle, measurement of the PTS using the PAA. (A) Rotational alignment of posterior tibial condyles with a difference of <7 mm. (B) Increased internal tibial rotation with ≥7 mm between the posterior tibial condyles. MA, mechanical axis; PAA, proximal anatomical axis; PTS, posterior tibial slope.

tibia. An x-ray reference sphere with a diameter of 25 mm was used. The PTS was measured using the MA and PAA as references, as displayed in Figure 2. The MA of the tibia in the sagittal plane is measured as a line connecting the midpoint of the medial tibial plateau and the midpoint of the tibial plafond.[30] The angle between a line tangential to the medial tibial plateau and a line orthogonal to the MA expresses the PTS. The PAA, as described by Yoo et al,[30] is defined as a line connecting the midpoint of the tibial shaft 5 and 15 cm below the joint line; the angle between a line tangential to the medial tibial plateau and a line orthogonal to the PAA expresses the PTS.[30] A circle tool that automatically displayed the midpoint was used to determine the midpoint of the medial tibial plateau, the tibial plafond, and the tibial shaft for radiographic measurements. Radiographs were measured twice, with the surgeon blinded to the previous result and at least 6 weeks apart, to estimate intraobserver reliability. All radiographs were analyzed by a trained orthopaedic knee surgeon (W.B.). To estimate interobserver reliability, the radiographs were measured by a second trained orthopaedic surgeon (P.M.). The measurements were performed with the Picture Archiving and Communication Systems (Xero Viewer; Agfa Health Care).

The data obtained were analyzed for differences in PTS configuration according to the different measurement techniques.

Statistical Analysis

Statistical analysis was performed with SPSS for Windows Version 28 (IBM Corp), and descriptive data were stated as the mean ± standard deviation (range). For parametric data, a 2-tailed *t* test was used. The intra- and interobserver reliability were calculated for measuring the PTS with the PAA and the MA using the intraclass correlation coefficient (ICC). According to the ICC values, the reliability was defined as poor (<0.5), moderate (0.5 ≤ ICC < 0.75), good (0.75 ≤ ICC < 0.90), or excellent (≥0.90). A linear correlation (Pearson correlation) was applied to detect correlations between the measurement methods.

In the current literature, no specific pathological threshold values have been published for the PTS measured using the MA. For the measurement with the PAA, PTS values ≥12° were interpreted as pathologic, as several studies have reported an increased risk for ACL graft insufficiency or ACL graft rerupture in patients with values exceeding this cutoff.[23,28] In the group with a distance of <7 mm between the posterior tibial condyles, different subgroups were defined with a lower limit of the PTS from which the PTS was assumed to be pathological when using the MA: group 1, PTS with MA ≥10° and PAA <12°; group 2, PTS with MA ≥10.5° and PAA <12°; group 3, PTS with MA ≥11° and PAA <12°; and group 4, PTS with MA ≥11.5° and PAA <12°. Moreover, the sensitivity, specificity, and accuracy of the PAA for screening of a pathological PTS (≥12°) were determined for each of these groups using the different thresholds of the MA as a standard for comparison.

TABLE 1
Patient-Specific Data[a]

	Value
No. of cases	196
Sex	
Female	59 (30.1)
Male	137 (69.9)
Age, y	37.1 ± 12.2 (14-66)

[a]Data presented as mean ± SD (range) or n (%) unless otherwise indicated.

TABLE 2
Mean PTS Values[a]

	Total (n = 196)	Women (n = 61)	Men (n = 135)
MA, deg	9.4 ± 3.8 (0.4 to 21.9)	9.7 ± 3.5 (0.8 to 17.9)	9.3 ± 3.9 (0.4 to 20.9)
PAA, deg	10.5 ± 3.5 (1.7 to 20.9)	10.8 ± 3.2 (1.7 to 17.5)	10.3 ± 3.8 (3.1 to 20.7)
Difference PAA – MA, deg	1.1 ± 1.2 (–2.4 to 4.1)	1.1 ± 1 (–0.7 to 4.1)	1 ± 1.2 (–2.4 to 4)

[a]Data are presented as mean ± SD (range). Women vs men: MA, P = .56; women vs men: PAA, P = .39. MA, mechanical axis; PAA, proximal anatomical axis; PTS, posterior tibial slope.

RESULTS

Radiographs with a distance between the posterior tibial condyles of ≥7 mm showed a mean difference between the measurement with the PAA and the MA of 1.9° ± 1.4° (n = 22); the mean difference for PTS between the PAA and the MA with overlapping of posterior tibial condyles of <7 mm was 1.1° ± 1.2° (n = 196). The difference between the 2 groups was significant (P = .001). In the group with <7 mm distance between the posterior tibial condyles, the median difference was 1.1° and in 25% the difference exceeded 2° with a maximum of 4.1°. When the distance was ≥7 mm, the median value was 1.9° and in 50% the difference in the PTS exceeded 2° with a maximum of 5.1°. Radiographs with ≥7 mm were excluded from further statistical analysis.

Patient-specific data are displayed in Table 1. The results of radiographic measurements are displayed in Table 2. The mean difference of the PTS between the MA and PAA was 1.1° ± 1.2° (range, –2.4° to 4.1°). No significant differences in the PTS could be detected between women and men. In 16% of the cases (n = 32), the PTS measured with the PAA showed smaller values, compared with the PTS according to the MA. In these 32 cases, the PTS (MA) showed values in the range between 9° and 14° in 56% of patients (n = 18).

The PTS measured with the MA and the PAA showed a strong linear correlation (Pearson r = 0.95; P < .001). With increasing PTS values measured with the MA, the difference between the PAA and the MA showed a tendency to decrease.

An excellent intraobserver reliability of 0.97 (95% CI, 0.96-0.98) was found using the ICC for the PTS measurement with the MA. The interobserver reliability was excellent with an ICC of 0.95 (95% CI, 0.93-0.96) for the PTS measurement with the MA. An excellent intraobserver reliability of 0.96 (95% CI, 0.95-0.97) was found using the ICC for the PTS measurement with the PAA. The interobserver reliability was excellent with an ICC of 0.91 (95% CI, 0.88-0.93) for the PTS measurement with the PAA.

The sensitivity, specificity, and accuracy for identifying pathological PTS values using the PAA for the different subgroups compared with the MA are shown in Table 3.

TABLE 3
Sensitivity, Specificity, and Accuracy for Detecting Pathologic PTS Values With PAA Versus MA[a]

	Sensitivity, %	Specificity, %	Accuracy, %
Group 1 (MA ≥ 10°; PAA < 12°)	73	98	86
Group 2 (MA ≥ 10.5°; PAA < 12°)	84	97	92
Group 3 (MA ≥ 11°; PAA < 12°)	87	93	91
Group 4 (MA ≥ 11.5°; PAA < 12°)	95	89	91

[a]MA, mechanical axis; PAA, proximal anatomical axis; PTS, posterior tibial slope.

DISCUSSION

The key finding of this study indicates that using the MA for measuring PTS is advantageous in reliably screening for pathological PTS values. Notably, the relationship between PTS measurements obtained from the PAA and the MA reveals outliers, and the observed differences are not consistently uniform. As the mean difference between the PAA and MA for PTS values that were analyzed in different publications ranges from 0.2° to 2.3°, with a mean difference of 1.2° (median, 1.1°),[9,11,15,30] the subgroups were designed to cover the area of PTS values measured with the MA from 10° to 11.5°. To the best of our knowledge, no cutoff values have been defined for PTS measurements of the MA in terms of risk of failure after ACLR. PTS values measured with the PAA were defined to be pathological when exceeding 12°, resulting in an increased risk for failure of ACLR.[1,14,23,28] In consequence, it could be assumed that there must exist a corresponding range of values from where the PTS has a pathological influence when measured with the MA. In the data provided in this analysis, it was not possible to declare a clear cutoff, but it was assumed that the PTS, when measured with the MA, can be interpreted as pathological when passing the 10.5° to 11° threshold. The subgroups aimed to cover this area of interest for PTS values measured with the MA as a reference. In this setting, when defining 10.5° or 11° as the pathological threshold for the PTS measured with the MA, 16% and 13%, respectively, would have been overlooked, as the PTS measured with the PA was <12°. Even with a comparatively high threshold of 11.5° (PTS with MA), 5% of the patients would have shown PTS values of <12° measured with the PAA. Therefore, screening for pathological PTS with techniques using the PAA on lateral radiographs of the tibia cannot be recommended, as this method failed to identify all cases with noticeably increased PTS values with the MA. In 16% of patients, the PTS measured with the MA showed even higher PTS values compared with the measurement according to the PAA. The presence of outliers, as indicated by the inconsistency in differences between the MA and PAA measurements, further supports the hypothesis that the PAA does not represent a reliable indicator for the relevant mechanical loading conditions of the tibia in the sagittal plane. The differences between the 2 methods could result from deformities of the distal tibia. A distal malalignment can have a major impact on the overall tibial alignment in the sagittal plane and cannot be detected on short lateral radiographs. This is in line with the findings of Hees et al,[15] as the PTS measured with the PAA tends to underestimate the PTS due to a tibial bowing, in contrast to measurements using the MA. Further, the tibial bowing angle correlated with the PTS referenced to the MA in a sagittal long lateral tibial radiograph. A comparable observation was evident in the data presented in the present investigation. With increasing PTS values for the MA, the difference between the PTS measured by the MA and the PAA showed a tendency to decrease, which may result from tibial bowing. Although the tibial bowing was not measured explicitly, the obtained measurements, as stated above, can be interpreted as pointing in this direction. Increasing tibial bowing will lead to an increasing dorsally directed angulation of the PAA in the lateral radiograph. Consequently, because of the change in the PAA, while the reference to the medial tibial plateau remains the same, the PTS will decrease. The measurement with the MA is not influenced by this effect. Because values of the PTS measured with the MA are usually lower, the PTS values of the PAA and the MA will converge.

Comparable data about differences between various reference axes for PTS measurement were published in a previous study. Dean et al[9] compared the values for the PTS between the measurement with the PAA, AA, and MA on full-length lateral tibial radiographs. When comparing the PAA and the AA in 21% of cases, the difference in PTS values was $>2°$; a difference of $\geq 2°$ was detected in 55% of cases when comparing PTS values measured with the PAA or the MA as a reference. This underlines the data presented in our study. An isolated measurement of the PAA for the screening of increased PTS values does not allow for the prediction of mechanical loading conditions in the sagittal plane, as this could be better estimated with the lateral MA of the tibia. Therefore, we recommend establishing the measurement of the MA on full-length lateral tibial radiographs as a standard for PTS measurement. To our interpretation, the mechanical loading conditions are of utmost importance—particularly when planning a corrective osteotomy. Comparable to the alignment analysis in the frontal plane, where the usage of the MA represents the gold standard, deformity analysis in the sagittal plane should also be performed using the MA as a reference for PTS measurement. This will decrease the risk of missing out on patients with deformities of the lower tibia influencing the PTS. In addition, when planning an osteotomy for PTS correction, a full-length lateral tibial radiograph is not dispensable to assess the consequences of the osteotomy for the sagittal plane alignment. An under- or overestimation of the PTS could lead to an under- or overcorrection in the case of slope-reducing osteotomy.

It remains unclear to what extent increased PTS values need to be corrected by osteotomy. However, there is increasing evidence showing that an increased PTS is a strong individual risk factor for ACLR failure because of rerupture or graft insufficiency.[19,21,23] Therefore, it is of utmost importance to identify patients at risk. When interpreting the measurement of the PAA for the PTS as a screening method, a sensitivity of 84% or 87%, assuming a PTS of 10.5° or 11°, respectively, measured with the MA as a threshold, indicates that a certain number of patients could not be identified correctly. On the other hand, 3 patients in the present study exhibited a PTS $>12°$ when measured with the PAA, while the measurement using the MA was $<10.5°$. This suggests that these patients may have a noncritical PTS in the mechanical analysis, even though they were identified as having pathological PTS in the proximal anatomic measurement. This could lead to an overestimation of the individual risk with the potential consequence of consecutive overtreatment. When the PAA exceeded 14°, there was no patient in the present study group with a PTS measured with the MA $<10.5°$. With a PTS (PAA) $<9°$, there were no cases with a PTS $>10.5°$ measured with the MA. Therefore, according to the data of the present study, PTS values $<9°$ and $>14°$ could be identified as a safe interpretation zone when using the PAA in clinical routine. In the transition area, when PTS measured with the PAA is between 9° and 14°, one must be cautious as the PAA is not the sole indicator of pathological PTS in this range of values. As mentioned earlier, in a total of 32 cases (16%), the measurement with the MA exhibited higher PTS values compared with the PAA. Among these cases, 56% (n = 18) showed this discrepancy when the PTS measured with the MA fell within the range of 9° and 14°. This finding underscores that the PAA does not accurately represent the mechanical loading conditions in the sagittal plane.

Another interesting finding of the present study was that a distance, between the posterior medial and lateral tibial condyle on a lateral radiograph of the tibia, of ≥ 7 mm resulted in an increased discrepancy between the measurement of the PTS using the PAA and MA. Hence, it is advisable to ensure that the distance between the posterior tibial condyles in lateral radiographs is minimized, ideally achieving an accurate superimposition of the posterior tibial condyles. Gwinner et al[13] reported a comparable recommendation using the femoral condyles as a reference. With an overlapping of ≥ 5 mm of the femoral condyles, there was a significantly higher probability that both raters exceeded a difference of 2° in their measurements. As shown in a recent study by Huettner et al,[17] malrotation can even occur within the knee joint itself. A broad variation of the individual knee version could be shown in their study. Therefore, it must be concluded that a correct alignment of the posterior femoral condyles does not automatically imply a correct rotational alignment of the posterior tibial condyles in the sagittal plane. The effect of rotational malalignment on PTS measurement was reported in previous publications. Kessler et al[18] and Weinberg et al[29] described an increase in PTS values in the case of internal tibial rotation due to changes in projection on the radiograph. Further, Weinberg et al recommend the use of the posterior tibial condyles as an anatomic landmark for rotational alignment control, too. The authors of the present publication concur that measuring the distance between the posterior tibial condyles is a more appropriate approach for achieving accurate alignment in lateral tibial radiographs when determining the PTS.

Limitations

One limitation of our study that must be mentioned is that the PTS values were analyzed in a mainly Caucasian, Central European population. In previous literature, it has been described that significant differences exist in PTS between ethnic groups.[4,5,22] In addition, these radiographs were all taken in an ACL injured patient collective. These patients are more likely to present a pathological PTS compared with a patient group without a history of ACL injury. This must be considered when transferring these results into clinical practice. In addition, the stated mean values could be interpreted as normal values. Moreover, the cutoff values described for the PTS alone could not be taken as the sole reason for a surgical correction. The recommendation for when an osteotomy for PTS correction should be performed is up to the individual's discretion. Together with other cofactors, PTS values should be seen as an element of the individual risk assessment that leads to a treatment recommendation. Further research is needed to provide evidence-based recommendations on the degree of the PTS that necessitates a correction osteotomy to significantly reduce the risk of failure after ACLR, as well as to identify which additional risk factors may further increase this risk.

CONCLUSION

Measuring the PTS using the MA was advantageous, as the measurement with the PAA did not identify all cases with sagittal alignment changes correctly. The proportion of patients with pathologically increased PTS not identified with the proximal anatomical measurement, reflected by the sensitivity, depended on the threshold value defined for the MA. Lateral radiographs showing an increased distance between the posterior tibial condyles indicated malrotation of the tibia, leading to measurement inaccuracy.

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Conclusion

The PTS plays an important role in the biomechanics and antero-posterior stability of the knee joint. Its osseous alignment has an impeccable influence in surgical procedures like ACL-R, as a steeper slope (commonly defined >12.0°) increases the re-rupture rate. The most used measurement methods are the PAA using a lateral knee radiograph and the MA on a full-length lateral tibial radiograph. It is said that the PAA misses to identify pathological PTS values, so this study focused on comparing the two measurement methods mentioned above. The results demonstrate that using the MA for pathological PTS screening is advantageous to the PAA, as the PAA fails to distinguish all patients with distal tibial malalignment. This results in discernibly increased slope measurements. The failure rate is dependent on the defined pathological cut-off value for the MA and therefore it is strongly recommended to determine PTS values on full-length lateral tibial radiographs in reference to the MA. The posterior tibial condyles on lateral radiographs must be evaluated carefully because an overlap of ≥7mm indicates malrotation and can lead to measuring inaccuracy. For a more promising surgical outcome it is advocated that future studies focus on identifying cut-off values for a pathological PTS measured with the MA and when a concurrent slope correction osteotomy is indicated.

Zusammenfassung

Der PTS spielt eine wichtige Rolle in der Biomechanik und antero-posterioren Stabilität des Kniegelenkes. Die knöcherne Ausrichtung hat einen immensen Einfluss auf operative Eingriffe wie eine vordere Kreuzbandrekonstruktion, da ein steiler Slope (meist definiert als >12.0°) die Re-Ruptur Rate erhöht. Die am häufigsten verwendeten Messmethoden sind die PAA am lateralen Knie Röntgen und die MA anhand eines seitlichen Röntgens der ganzen Tibia. Es wird angenommen, dass die PAA pathologische PTS-Werte übersieht, weshalb diese Studie die zuvor beschriebenen Messmethoden miteinander vergleicht. Die Resultate zeigen, dass die MA bei der Detektion eines pathologischen PTS der PAA überlegen ist, da nicht alle Patienten mit einer Deformität der distalen Tibia mit der PAA identifiziert werden, was wiederum zu einer erkennbar erhöhten Slope Messung führt. Daher, dass die Misserfolgsquote abhängig von dem zuvor pathologisch definierten Grenzwert für die MA ist, ist es dringend erforderlich den Wert des PTS anhand einer lateralen Ganzbeinaufnahme der Tibia in Referenz zur MA zu definieren. Die posterioren Kondylen der Tibia müssen auf seitlichen Röntgenbildern genau beurteilt werden, da eine Überlappung von ≥7mm auf eine Malrotation hinweist und zu einer Messungenauigkeit führen kann. Für ein vielversprechendes chirurgisches Ergebnis sollten zukünftige Studien sich darauf fokussieren eine Obergrenze für einen pathologischen PTS, gemessen mit der MA, zu identifizieren und eruieren ab wann eine einhergehende Slopekorrektur notwendig ist.

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Abbreviation Index

2D	Two Dimensional
3D	Three Dimensional
AA	Anatomical Axis
ACL	Anterior Cruciate Ligament
ACL-R	Anterior Cruciate Ligament Reconstruction
ATC	Anterior Tibial Cortex
CT	Computed Tomography
FPAA	Fibular Proximal Anatomical Axis
FSA	Fibular Shaft Axis
HTO	High Tibial Osteotomy
ICC	Intraclass Correlation Coefficient
MA	Mechanical Axis
MRI	Magnetic Resonance Imagine
PCL	Posterior Cruciate Ligament
PTC	Posterior Tibial Cortex
PTS	Posterior Tibial Slope
TKA	Total Knee Arthroplasty
TS	Tibial Slope
PAA	Proximal Anatomical Axis

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Equity Ratio

My equity ratio for this research project is as follows:

Data acquisition

I collected the data for the present research project. I have done the measurements and evaluations as one of three independent observers. The patient pool was provided by the Department of Sports Orthopaedics and Joint Surgery at the Orthopaedic Hospital in Markgroeningen.

Experimental setup

Dr. med. Philipp Mayer and I composed the experimental setup in cooperation.

Data analysis and drafting of manuscript

The analysis of the gathered data was mainly done together with my co-author Dr. med. Philipp Mayer. He performed the primary framework of the manuscript. I subsequently added and corrected the manuscript. The finishing of the manuscript was constructed by all authors. The admission to the journal 'Orthopaedic Journal of Sports Medicine' was done by Dr. med. Philipp Mayer, as well as the requested modifications by the journal, however those were pre-decided with me.

The previous mentioned assessment regarding my equity ratio was amicably coordinated with all the participated co-authors of this paper.

28.01.2025, ______________________
Date, Signature Doctoral Candidate

28.01.2025, ______________________
Date, Signature Co-Author

Eidesstattliche Versicherung

Ich versichere ausdrücklich, dass ich die Arbeit selbständig und ohne fremde Hilfe, insbesondere ohne entgeltliche Hilfe von Vermittlungs- und Beratungsdiensten, verfasst, andere als die von mir angegebenen Quellen und Hilfsmittel nicht benutzt und die aus den benutzten Werken wörtlich oder inhaltlich entnommenen Stellen einzeln nach Ausgabe (Auflage und Jahr des Erscheinens), Band und Seite des benutzten Werkes kenntlich gemacht habe. Das gilt insbesondere auch für alle Informationen aus Internetquellen.

Soweit beim Verfassen der Dissertation KI-basierte Tools („Chatbots") verwendet wurden, versichere ich ausdrücklich, den daraus generierten Anteil deutlich kenntlich gemacht zu haben. Die „Stellungnahme des Präsidiums der Deutschen Forschungsgemeinschaft (DFG) zum Einfluss generativer Modelle für die Text- und Bilderstellung auf die Wissenschaften und das Förderhandeln der DFG" aus September 2023 wurde dabei beachtet.

Ferner versichere ich, dass ich die Dissertation bisher nicht einem Fachvertreter an einer anderen Hochschule zur Überprüfung vorgelegt oder mich anderweitig um Zulassung zur Promotion beworben habe.

Ich erkläre mich damit einverstanden, dass meine Dissertation vom Dekanat der Medizinischen Fakultät mit einer gängigen Software zur Erkennung von Plagiaten überprüft werden kann.

28.01.2025
Datum

Unterschrift

Acknowledgement

This acknowledgment goes out to all the people and institutions that played a part in creating this dissertation. First, I would like to thank PD. Dr. med Tim Rolvien for the academic supervision. I would also like to express my gratitude to my co-supervisor Prof. Dr. med Philipp Schuster, who supported me throughout the way creating this dissertation and granted an uncomplicate, straightforward and highly academic cooperation.

Further, a huge thank you to my Co-author Dr. med Philipp Mayer, without whom the whole project would not have been possible. Thank you for your support and expertise regarding the topic. For me it was an absolute pleasure to work on the project with you!

I would also like to thank Dr. med Jörg Richter for providing me with the patient data and making his Centre for Sports Orthopaedics and Special Joint surgery in Markgroeningen available to me for the research of this study.