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Ankle Alignment on Lateral Radiographs: Part 1: Sensitivity of Measures to Perturbations of Ankle Positioning

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Abstract

Background—In ankles with end-stage osteoarthritis or with total ankle replacement (TAR), radiographic landmarks based on joint surface morphology are usually obscured and thus inadequate for radiographic measurement. Furthermore, because of difficulty in reproducibly positioning the ankle for a standing radiograph, any radiographic measure to accurately describe ankle alignment needs to tolerate perturbations of ankle positioning in clinical radiographs. To identify a radiographic measure of antero-posterior (AP) tibial-talar alignment that meets those requirements, three candidate measures were compared by means of sensitivity to perturbations of ankle positioning.

Methods—Ten cadaver ankles had lateral radiographs taken while varying ankle position, at nine prespecified positions in the transverse plane and at seven positions in the sagittal plane. The AP tibial-talar alignment was quantified by three candidate measures. Sensitivity to changes of ankle position in each plane was then compared across the measures.

Results—With the tibial axis-talar ratio (T-T ratio: the ratio into which the mid-longitudinal axis of the tibial shaft divides the longitudinal talar length), sensitivity to ankle positional changes in either plane was lowest, with errors associated with 10 degrees of ankle malpositioning being around 2.2%. The posterior line-talar ratio (P-T ratio: a similar ratio, but using the posterior longitudinal line of the tibial shaft) showed higher sensitivity in the transverse plane than the T-T ratio, though the associated errors in either plane were nearly comparable. The tibial axis-lateral process distance (T-L distance: the perpendicular distance from the tibial axis to the tip of the lateral talar process) showed highest sensitivity in both planes.

Conclusions—The T-T ratio tolerated perturbations of ankle positioning best among the tested measures. This measure is potentially applicable to clinical radiographic measurement when determining the AP tibial-talar alignment in ankles with articular degeneration or TAR. The P-T ratio also appears to have reasonable tolerance.

Keywords

ankle; alignment; radiographic measurement; cadaver experiment

Introduction

Articular degeneration with ankle osteoarthritis often involves ankle malalignment, including anterior or posterior subluxation of the talus under the tibia. Anterior angular deformity of the distal tibia, either primary or post-traumatic, has been described as causing increased articular

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contact stress in the anterior ankle.[6,8] Likewise, posterior deformity likely causes the converse problem. Antero-posterior (AP) ankle malalignment appears to be an important determinant of mechanical stress in the human ankle joint, and has been implicated in accelerated rates of degeneration.

In total ankle replacement (TAR), restoring the anatomical orientation of the talus and tibia is considered vital to good long-term outcomes.[1,2,4] AP ankle malalignment is one possible cause of premature implant failure, and unfavorable mechanical effects of AP implant malpositioning have been described in cadaver-based experimental studies.[5,7] However, one of the reasons this problem has not yet been well studied is because of a lack of reliable means to assess AP ankle alignment.

On ankle radiographs with either severe articular degeneration or with TAR implants, radiographic landmarks based on ankle joint surface morphology are usually obscured and thus inadequate for radiographic measurement. Ankle alignment in such situations must be determined without relying on those landmarks. Furthermore, for a clinical standing radiograph, reproducibly positioning the ankle in any orientation is difficult to achieve, especially in the setting of patients with pain on weight bearing or with restricted joint motion. Any radiographic measure to accurately describe ankle alignment needs to tolerate perturbations of ankle positioning possibly involved in clinical radiographs.

In this study, to identify a radiographic measure of AP tibial-talar alignment that meets those requirements, three candidate measures were compared by means of sensitivity to perturbations of ankle positioning. A cadaver experiment was designed to create highly controlled malpositionings of the ankle, similar to those we have observed in clinical practice. The sensitivity of each measure to changes of ankle position during radiography was then explored. In addition, the possible effect of height of tibial landmarks used to make these measurements was evaluated.

Methods

Ten fresh-frozen human ankle specimens were obtained from five donors (mean age 81, range 66–100) at autopsy. No deformities, contractures, or articular degeneration were evident on radiographic or manual inspection. Each specimen was thawed at room temperature before testing. For mounting in the testing apparatus, a plastic intramedullary rod was inserted to the tibial canal and secured with polymethylmethacrylate.

A specimen was mounted in a custom specimen table placed in a digital radiographic device (Siemens Co., Munich, Germany). This specimen table allowed ankle position control in both the transverse and sagittal planes under a consistent stabilizing force (19.6 N) across the ankle joint (Fig. 1). Sagittal ankle position was controlled by changing the inclination of the tibial intramedullary rod in dorsi- or plantar flexion, and transverse ankle position was controlled by rotating the whole specimen on a turntable. Because the ankle was positioned to align with the transverse rotation axis of the turntable, ankle position was controllable while maintaining a certain positional relationship between the ankle and the radiographic device.

Each specimen was subjected to a series of lateral radiographs at nine ankle positions in the transverse plane and at seven positions in the sagittal plane, to simulate various ankle positions on standing radiographs. The transverse ankle positions were −20, -15, -10, -5, 0, +5, +10, +15, and +20 degrees of internal rotation (the position of 0-degree rotation was identified as the position when the longitudinal axis of the foot was perpendicular to the x-ray beam). For those radiographs, the sagittal ankle position was maintained in 0-degree plantar flexion (identified as the position when the tibial intramedullary rod was perpendicular to the floor), which was defined as the standard sagittal position.

Those radiographs were then utilized to determine the standard transverse position, the optimum transverse position for taking a lateral ankle image. This position was identified by the best agreement of the AP orientation between the lateral and medial talar condyles. On each radiograph, the center of each condyle was identified as the arc center of the articular contour, and AP relative orientation between the condyles was measured. This measure was plotted for the nine transverse positions for each specimen. This relationship theoretically describes a segment of a sine curve, as the displacements were rotational. However, because the displacements were relatively small, that relationship was approximated to a linear trend line, using which a specimen specific optimum transverse position was calculated. This position averaged across 10 specimens at 4.9 degrees of internal rotation (range −5.4 to 16.6), and the 5-degree internal rotation position was accordingly chosen as the standard transverse position.

Next, each specimen was subjected to lateral radiographs at seven sagittal ankle positions; in -10, -5, 0, 5, 10, 15, and 20 degrees of plantarflexion. For those radiographs, the transverse position was maintained at the standard transverse position of 5-degree internal rotation.

Radiographic Measurement

For the talus, an intersection between the posterior subtalar articular contour and the postero-superior contour of the calcaneus was defined as the posterior talar point (point A in Fig. 2a). A line through point A parallel to the floor was drawn as a talar reference line. The vertical projection of the most anterior aspect of the talus onto the talar reference line was defined as Point B, and the length of line AB was measured as a longitudinal talar length. Point C was denoted as the tip of the lateral talar process.

For the tibia, anterior and posterior surface points of the distal tibial shaft were determined at 5 and 10 cm above the ankle, and the longitudinal line bisecting them was defined as the distal tibial axis (DTA in Fig. 2b). The posterior tibial line (PTL) was identified as a line though the posterior tibial shaft points.

The AP tibial-talar orientation was then quantified by three candidate measures without using radiographic landmarks based on ankle joint surface morphology:

1. **Tibial axis - talar ratio** (T-T ratio, Fig. 3a): The intersection of the DTA with the talar reference line was defined as point D. The part of length AD to length AB was then calculated.

   T-T ratio (%) = (AD / AB) × 100

2. **Posterior line - talar ratio** (P-T ratio, Fig. 3b): The intersection of the PTL with the talar reference line was defined as point E. The part of length AE to length AB was then calculated. When the PTL was posterior to the point A, this measure was recorded as a negative value.

   P-T ratio (%) = (AE / AB) × 100

3. **Tibial axis - lateral process distance** (T-L distance, Fig. 3c): The perpendicular distance from DTA to point C was measured and normalized to the talar length AB. When point C was posterior to DTA, this measure was recorded as a negative value.

   T-L distance normalized to the talar length AB (%) = (Perpendicular distance from DTA to point C / AB) × 100

For the radiographs in the standard position, in addition to these standard methods, each measure was recalculated with modified versions of DTA or PTL. To assess the effect of the tibial shaft length for measurement, extended versions of DTA and PTL were identified using tibial shaft points 5 and 15 cm above the ankle. To estimate the potential error from the conical shape of the distal tibia shaft, each measure, using both the regular and extended lengths, was recalculated with a controlled error of distal tibial point height (1cm lower than the regular height).

Radiographic measurement was performed with use of a custom digitizing program based on PV-WAVE® (Version 6.21, Visual Numerics, Inc., San Ramon, CA). This program prompts the user to mouse-click on prescribed landmarks on each digital image, and the on-screen coordinates of these landmarks are then used to calculate the radiographic measures, similar to the program in a previous study.[3] A single orthopaedic surgeon measured all radiographs twice; the mean value was recorded as the measure, and the absolute difference was the intra-observer error. A secondary observer repeated every measurement for the radiographs in the standard position, and the absolute difference between that and the average of the first was the inter-observer error.

Data Analysis

Sensitivity to transverse positional changes was quantified as the greatest difference across the nine transverse positions (Fig. 4), and this value was compared across the measures. The mean value of the absolute differences of output associated with 10 degrees of internal- or external rotation from the standard position was recorded as the error with 10-degree ankle malpositioning. This parameter was averaged across specimens, in order to estimate the amount of possibly involved errors associated with perturbations of ankle positioning in clinical settings. Sensitivity to sagittal positional changes was similarly analyzed.

For each measure, the effect of tibia shaft length on reproducibility was explored by comparing intra- and inter-observer errors between the regular and extended lengths. The potential error with 1cm lower distal tibial point height was compared across the measures, as well as between the regular and extended lengths.

Statistical analysis were performed by a repeated measures MANOVA; pairwise comparisons were reported only if the global test was significant at $p = 0.05$.

Results

In the standard position, the AP tibial-talar measure averaged 33.4 ± 3.3 % (mean ± standard deviation) for the T-T ratio, 9.9 ± 4.5 % for the P-T ratio, and 8.6 ± 1.0 % for the T-L distance (Table 1).

Sensitivity to transverse positional changes was lowest with the T-T ratio and second lowest with the P-T ratio, and highest with the T-L distance (Table 2, $p < 0.02$, for each pairwise comparison). Error with 10-degree malpositioning was 2.1% with the T-T ratio, 2.8% with the P-T ratio, and 5.8% with the T-L distance.

The sensitivity to sagittal positional changes with either the T-T ratio or the P-T ratio was lower than with the T-L distance (each $p < 0.001$). Error with 10-degree malpositioning was 2.3% with the T-T ratio, 2.4% with the P-T ratio, and 6.0% with the T-L distance.

With every measure, the intra-observer error averaged 1.3% or less, and the inter-observer error was 2.7% or less (Table 3). Errors with the extended tibial shaft length were almost equivalent to those with the regular length. Errors with 1cm lower distal tibial point height averaged 2.9% or less with every measure, almost equivalent to inter-observer error with either tibia shaft length.

Discussion

The T-T ratio was associated with the lowest sensitivity to changes of ankle position in both the transverse and sagittal planes, suggesting that this measure tolerates perturbations of ankle positioning best among the tested measures. A plausible explanation for the lower sensitivity relates to the centricity of the chosen anatomical landmarks. The projection of either the posterior edge of the talocalcaneal joint surface or the talonavicular joint surface in the transverse plane approximates an arc. The centers of both arcs are in the middle of the talus where the central longitudinal tibial axis usually falls. Probably because of this feature, the relative position of the tibial axis between those two talar landmarks changed minimally with rotational displacement in the transverse plane. The lower sensitivity with sagittal positional changes is thought to relate to the orientation of the ankle motion axis that approximates on the talar reference line. Under this setting, a change of ankle flexion causes only a slight migration of the intersection of the tibial axis with the talar reference line. Under clinical settings, AP tibial-talar alignment will be most accurately determined with use of this measure.

The P-T ratio was more affected by transverse positional changes than the T-T ratio. The reason for this relates to defining the posterior tibial line – which appears to be relatively sensitive to transverse rotational position of the tibia. However, the error associated with small amount of ankle malpositioning in either plane is estimated nearly comparable to one with the T-T ratio. Because identifying the posterior tibial line is relatively simple, the P-T ratio potentially serves as a quick measure to assess AP tibial-talar alignment, especially when focusing on the intersection of the posterior tibial line with the posterior subtalar facet.

The T-L distance was the most sensitive to ankle malpositioning. The location of the lateral talar process, located approximately 2 cm lateral to the central longitudinal tibial axis and inferior to the ankle motion axis, is probably responsible for this higher sensitivity. This landmark appears to be inadequate for determining the AP relative position of the ankle when ankle position is not perfectly controlled. The T-L distance may not be reliable in clinical settings, unless the ankle can be placed reproducibly in exactly the same transverse and sagittal orientation.

The length of the distal tibial shaft for determining the tibial lines (10 cm) was chosen because this length is routinely captured on lateral ankle radiographs in our clinic. The results demonstrated that extending this length to capture a central tibial point (15 cm above the ankle) did not improve reproducibility of any measure. This relatively short tibial length seems to be acceptable. The potential effect with the controlled error of distal tibial point height was essentially equivalent to inter-observer error. The effect of the conical shape of the distal tibial shaft seems to not substantially impact the outcomes, suggesting that the 5 cm height for the distal tibial landmark is satisfactory.

In conclusion, among the tested measures, the T-T ratio appears to have the best tolerance to perturbations of ankle positioning possibly involved in clinical radiographs. This measure is potentially applicable to radiographic measurement of AP tibial-talar alignment. In the clinic, to quickly detect possible anterior talar subluxation, assessing the AP orientation of the posterior longitudinal tibial line relative to the posterior subtalar joint is potentially helpful. Use of the tip of the lateral process of the talus to determine the relative AP position of the ankle is not reproducibly controlled.

Acknowledgements

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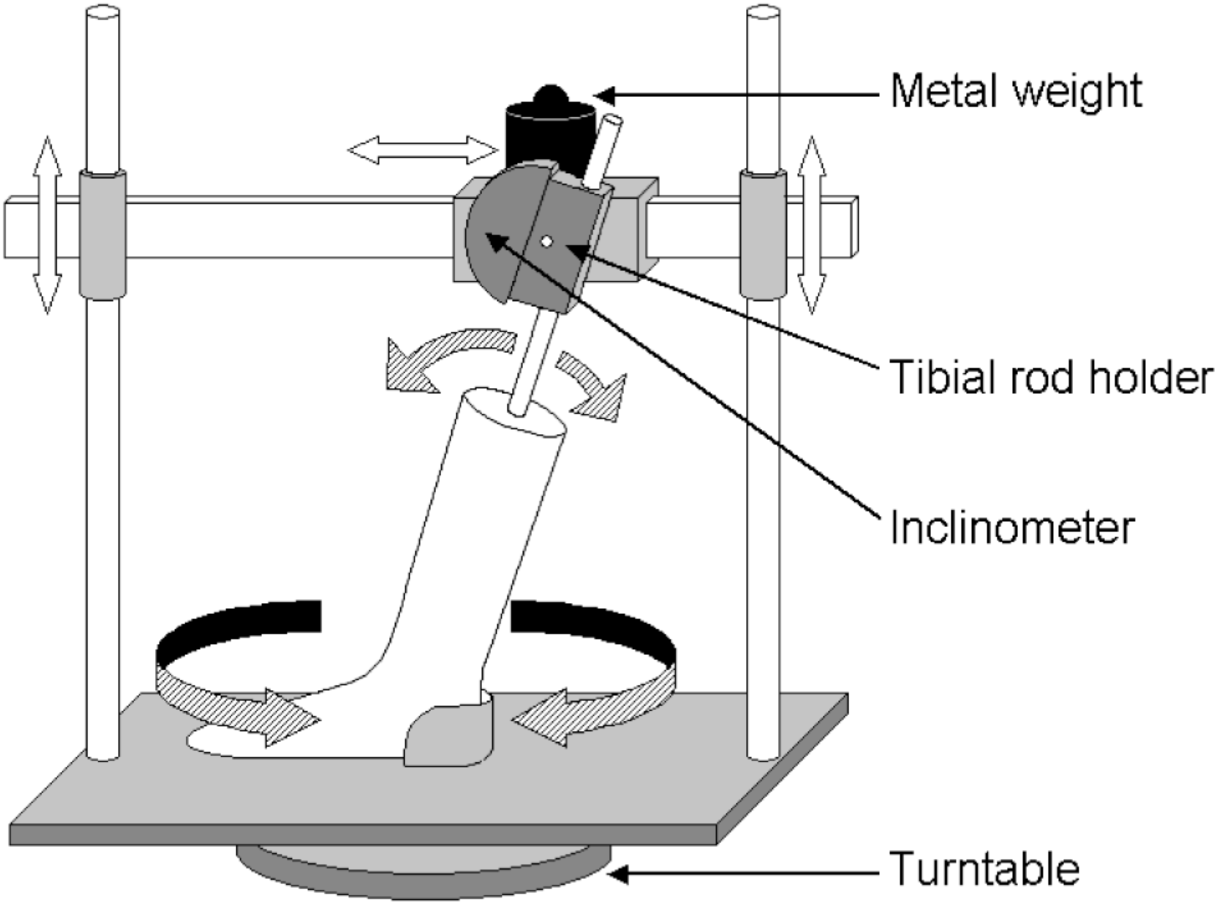

Fig. 1.

A schematic illustration of the custom specimen table. The tibial rod holder secures the tibial shaft with a predetermined sagittal inclination, while translation of this holder in both anterior/posterior and proximal/distal directions (white arrows) is unrestricted. The metal weight provides a consistent stabilizing force across the ankle (19.6 N). The turntable on which the foot is fixed with a heel-cup and Velcro tapes allows control of internal/external rotation of the specimen. As a result, ankle position in either transverse or sagittal plane (shaded arrows) can be controlled while maintaining a specific positional relationship of the ankle in a radiographic device.

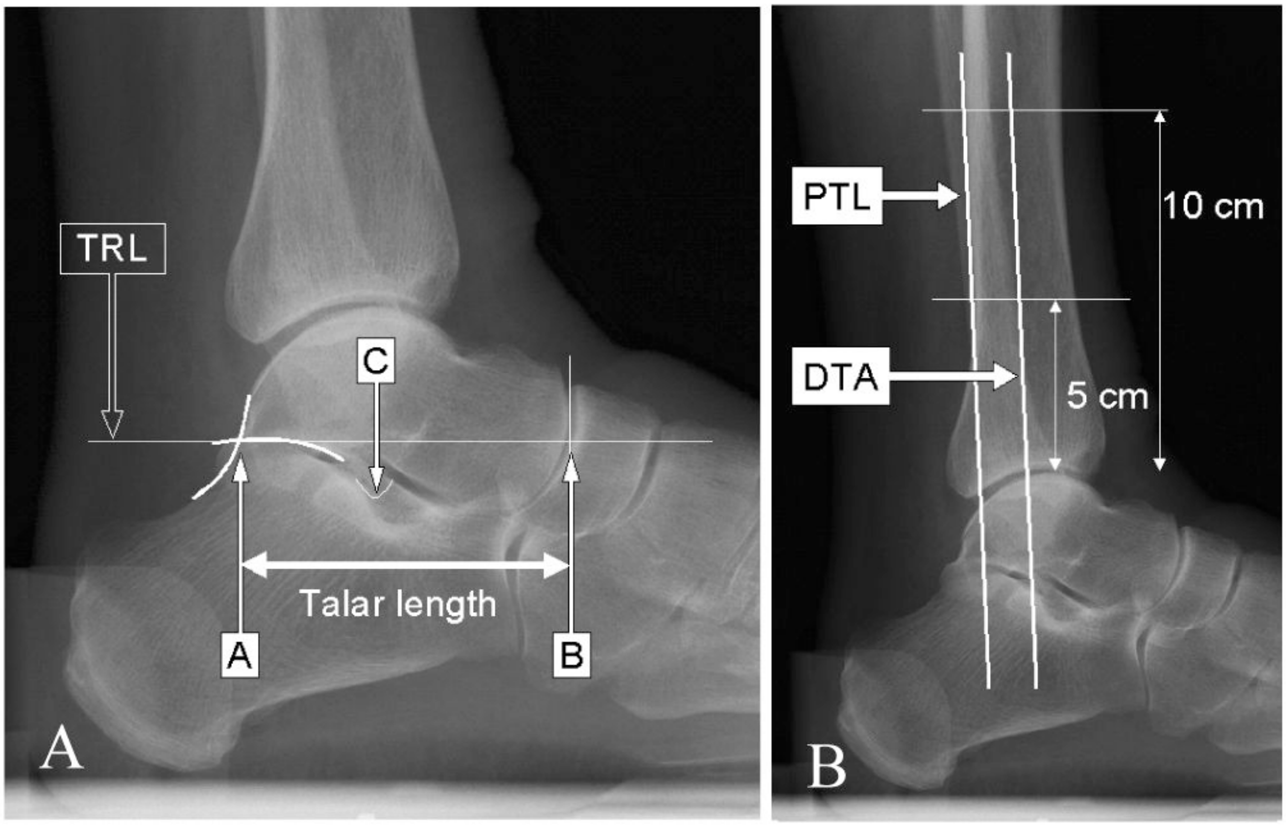

Fig. 2.

Radiographic landmarks. A) For the talus, the posterior talar point (point A) is identified as the intersection between the contours of the posterior subtalar articular surface and the postero-superior cortex of the calcaneus. The talar reference line (TRL) is a line drawn through point A parallel to the floor. Point B is identified as a vertical projection of the most anterior aspect of the talus onto the TRL, and length AB is the longitudinal talar length. Point C is the tip of the lateral talar process. B) For the tibia, the distal tibial axis (DTA) is a longitudinal mid-bisecting line of the distal tibial shaft determined at 5 and 10 cm above the ankle. The posterior tibial line (PTL) is a longitudinal line along the posterior tibial shaft surface, determined at those same heights.

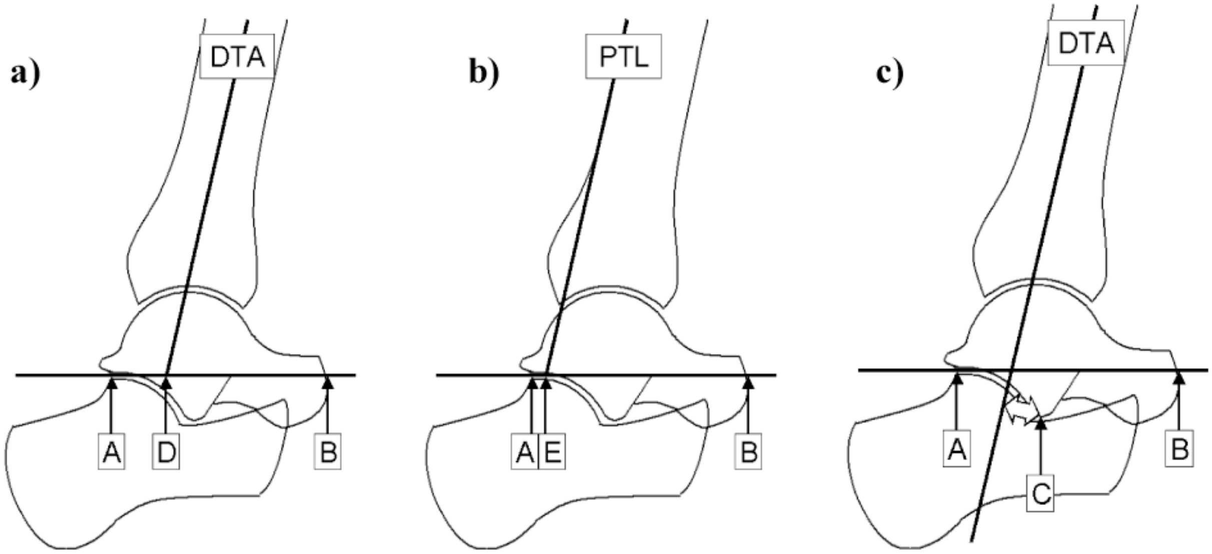

Fig. 3.

Schematics for candidate radiographic measures; a) the tibial axis-talar ratio (**T-T ratio** = AD / AB × 100), b) the posterior tibial line-talar ratio (**P-T ratio** = AE / AB × 100), and c) the tibial axis - lateral process distance normalized to the longitudinal talar length (**T-L distance** = Perpendicular distance from DTA to point C / AB × 100).

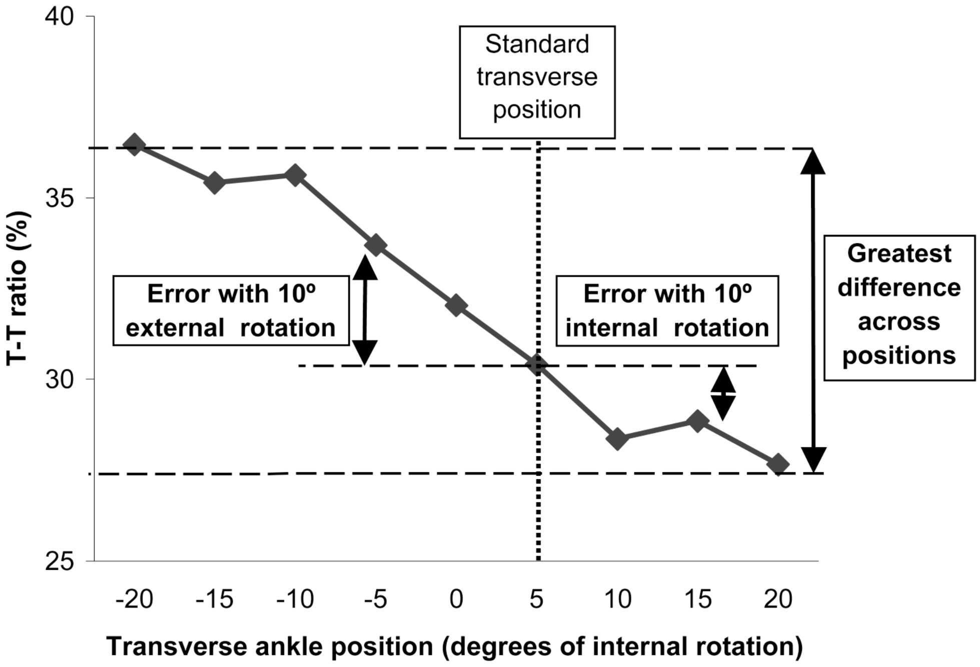

Fig. 4.

Typical relationship between transverse ankle positions vs. T-T ratio in a single specimen. The greatest absolute difference of output across the nine transverse positions is a parameter for assessing sensitivity to changes of the transverse ankle position. The mean value of the absolute differences of output associated with 10 degrees of internal- or external rotation from the standard position is the error with 10-degree ankle malposititining.

Table 1

Outcomes in the standard position (n = 10)

Type of measure	Average (mean ± SD)	Smallest	Largest
T-T ratio (%)	33.4 ± 3.3	27.7	38.1
P-T ratio (%)	9.9 ± 4.5	4.5	16.8
T-L distance (%)	8.6 ± 4.6	0.1	15.2

Table 2

Sensitivity to changes of ankle position (mean ± SD, n = 10)

Type of measure	Sensitivity to transverse changes			Sensitivity to sagittal changes		
	Greatest difference		Error with 10° malpositining	Greatest difference		Error with 10° malpositining
T-T ratio (%)	8.0 ± 2.3	*	2.1 ± 0.6	6.0 ± 2.5	**	2.3 ± 1.1
P-T ratio (%)	10.0 ± 4.0	**	2.8 ± 1.4	5.5 ± 1.9	**	2.4 ± 1.5
T-L distance (%)	26.5 ± 4.9		5.8 ± 1.3	17.4 ± 3.8		6.0 ± 1.3

[*] $p < 0.02$

[**] $p < 0.001$

Table 3

Effect of tibial landmark height (mean ± SD, n = 10)

Type of measure	Tibia length	Intra-obsrver error	Inter-observer error	Error with lower distal points
T-T ratio (%)	Regular	1.0 ± 1.2	2.4 ± 1.2	2.6 ± 1.1
	Extended	1.1 ± 1.2	2.0 ± 1.5	2.7 ± 0.7
P-T ratio (%)	Regular	1.3 ± 1.6	2.6 ± 1.5	1.3 ± 0.7
	Extended	1.7 ± 1.5	2.3 ± 1.2	0.9 ± 0.9
T-L distance (%)	Regular	1.1 ± 1.0	2.7 ± 1.7	2.9 ± 1.2
	Extended	1.4 ± 1.1	2.5 ± 1.3	2.9 ± 0.8