A COMMON REFERENCE FRAME FOR DESCRIBING ROTATION OF THE DISTAL FEMUR

A CT based kinematic study

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ABSTRACT

Understanding rotational alignment of the distal femur is key in the field of knee surgery. Errors in horizontal plane position of the femoral component in total knee arthroplasty are a major source of failure. Despite many reference axes have been described in the past, there is still disagreement about their value and mutual angular relationship. Our aim was to validate a geometrically defined reference axis against which the surface derived axes can be compared in the horizontal plane.

12 Cadaver specimens were CT scanned after rigid fixation of optical tracking devices to the femur and the tibia. Three-dimensional reconstructions were made for determination of anatomic surface points and geometrical references. The spatial relationships between femur and tibia in full extension and 90° of flexion were examined, with the use of an optical infrared tracking system. After coordinate transformation of the described anatomic points and geometrical references, the projection of the relevant axes in the horizontal plane of the femur could be mathematically achieved.

Inter- and intra-observer variability in the three dimensional CT reconstructions revealed angular errors ranging from 0,16° to 1,15° for all axes except for the trochlear axis displaying an inter-observer error of 2°. With the knees in full extension, the femoral transverse axis, connecting the centres of the best matching spheres of the femoral condyles, almost coincided with tibial transverse axis (-0,8°, Std 2,05°). At 90° of flexion, this femoral transverse axis was orthogonal to the tibial mechanical axis (0,2°, Std 3,66). Of all surface derived axes, the surgical transepicondylar axis had the closest relationship to the femoral transverse axis after projection on the horizontal plane of the femur (0,21°, Std 1,77°). The posterior condylar line was the most consistent axis with the smallest standard deviation (range -2,96° to -0,28°, Std 0,77°); the trochlear antero-posterior axis was the least consistent axis with the highest standard deviation (range -10,62° to 11,67°, Std 6,12°). The orientation of both the posterior condylar line and the trochlear antero-

posterior axis (p=0,001) showed a trend towards internal rotation with valgus coronal alignment.

Given the variable mutual angular relationships of these reference axes amongst individuals, the use of a single reference axis in choosing rotational alignment of the femoral component is discouraged and combined used is advised.

INTRODUCTION

The description of the geometry of the distal femur and the proximal tibia has received a lot of attention in the orthopaedic literature, not to he least because of the impact of decent three- dimensional insight on the outcome of surgical procedures. The geometry of the proximal tibia and the distal femur is intimately linked with the biomechanics of the tibiofemoral and the patellofemoral joint. In the field of total knee arthroplasty, the positioning of the implants in the horizontal plane is referred to as 'rotational alignment'. Poor outcomes and major complications have been linked directly to mistakes in the rotational position of the implants. [1-10]

Despite the fact that the clinical importance of correct rotational alignment cannot be overestimated, the dilemma of choosing the correct surgical references remains unsolved. For the rotational alignment of the femoral component, two systems prevail. In the "dependent resection", or tensioned gaps technique, the surgeon performs ligamenteous release to balance the knee in extension, followed by a resection of the posterior femoral surfaces parallel to the cut tibial surface, after applying equal loads to the medial and lateral compartment. [11,12] In the "measured resection" technique, a surface derived reference axis of the femur is used as a guide to determine the position of the femoral component in the horizontal plane. As several authors have claimed to have found the best reference axis, disagreement rules. The surface derived reference axes include the posterior condylar line

(PCL) [13,14], the surgical transepicondylar axis (surg TEA) [15-17], the anatomic transepicondylar axis (anat TEA)[18], and the trochlear antero-posterior axis (TRAx) [19].

Four obstacles interfere with surgical consistency: the semantic confusion over the definition of the 'correct axis', the natural variability of the reference axes, the inter- and intra-observer variability in the intra-operative determination of these references, and the practical execution of the cuts.

There is a distinct difference between the 'desired' alignment in the horizontal plane of the femoral component and the 'natural' alignment the distal femur. This divergence can be explained by the fact that the natural tibial plateau has a varus configuration [20]. The perpendicular coronal cut of the tibia will change this angle. Consequently, the femoral component will not be correctly aligned in flexion if it follows the natural surface anatomy. A rotational compensation to the same degree as the correction of the tibial cut in the coronal plane will generally be advocated. Consequently, as the literature refers to 'correct' horizontal plane alignment of the femoral component, the authors always refer to the 'adapted' alignment of the femoral component in the horizontal plane, which is different from the natural situation.

The numerous studies that have been dedicated to the comparison of axes, relevant for describing rotational alignment, all used mutual comparison between the above-mentioned references. [10,14-19,21-23] It is obvious why these axes have been selected, given the fact that surface points are accessible for palpation during surgery and thus clinically relevant. From a methodological standpoint however, the results are difficult to compare, given the absence of a fixed reference frame.

In the study conducted, we wanted to include additional information for improving the understanding of the three-dimensional relationships of the distal femur. We did so by including a geometrically defined reference axis, based upon previously published anatomical descriptions of the distal femur [24] and the proximal tibia [25]. Also, we used the dependent relation between femur and tibia in extension and flexion, to validate this geometrical axis, respectively called the femoral transverse axis (FTAx) and tibial transverse axis (TTAx).

The aim of this study is three-fold:

1. To determine the natural angular variability of previously studied surface derived axes (PCL, anat TEA, surg TEA, TRAx) as compared to FTAx, projected on the horizontal plane of the femur. The surface derived axis with the smallest variability is theoretically the most useful axis for surgical reference.

2. To measure the angle between FTAx and TTAx projected on the horizontal plane of the femur with the knee extended. As there is no rotational freedom between tibia and femur in full extension, this is a reliable position to measure the rotational relation between the two bones. If they are parallel in the horizontal plane, these axes can be validated as reliable rotational landmarks.

3. To determine the relation between the aforementioned femoral axes and the tibial mechanical axis at 90° of flexion. It is hypothesized that the FTAx will be perpendicular to this tibial mechanical axis, meaning neutral varus/valgus alignment at 90° of flexion.

MATERIALS AND METHODS

After consent of the ethical committee, 12 cadaver limbs were disarticulated at the level of the hip in 10 subjects (one matched pair, 10 non-matched). The specimens were deep frozen and optic stereotactic reference frames were rigidly attached. Volumetric CT scans on a 64-row multidetector computed tomography (MDCT) scanner (General Electric Lightspeed VCT, Milwaukee, WI) were performed using the following settings: 120 kVp, 450mA; Rotation time 0.5 sec; Pitch 0.516/1 Speed 20.62 mm per rotation; helical thickness

1.25 mm; Interval 0.8 mm. The CT scan data were fed into a three-dimensional software system (Mimics 11.02 and its MedCAD module, Materialise, Haasrode, Belgium) for further determination of relevant axes and surface points. Important surface landmarks were identified, using the quantitative morphologic description by LaPrade et al [26, 27]. Geometrically important points like the centre of the hip or the centre of the femoral condyles were determined by fitting a sphere in the outer surface mask of the respective structures.

A repeatability analysis was done on the first six specimens to evaluate the reliability of localizing the bony landmarks used to define the four major rotational axes and the FTAx. Three observers (DV,LL and JV) used bone surface reconstructions of the scanned joints to identify the landmarks three times with a minimum interval of one week (for intraobserver precision) and independently (for interobserver precision). Based on the recorded differences in position for each landmark between repeated measurements and between observers, the angular deviation for each axis with respect to its average orientation can be calculated. Methodological analysis was carried out as described by Bland and Altman[28]

The Cartesian coordinate system of the CT data was transformed into a new coordinate system for the femur and the tibia. The horizontal plane of the femur was defined as the plane perpendicular to the mechanical axis of the femur and comprising the centre of the knee. The centre of the knee was defined as the most posterior point of the trochlear groove (top of the femoral notch). The femoral transverse axis (FTAx) connects the centres of the two best matching spheres of the medial and lateral femoral condyle. The anat TEA connects the medial epicondyle with the lateral epicondyle. The surg TEA connects the medial sulcus with the lateral epicondyle. The TRAx connects the cranial and caudal deepest point of the trochlear groove. (Fig 1) At the tibia, the medial condylar centre and the lateral condylar centre was computed according to the description of Cobb et al., fitting the best matching circle to the cortical outline of the proximal tibia, 20 mm below the tibial spines.

[25] The line connecting the medial and lateral condylar centre (defined as the 'anatomical tibial axis' in Cobb's paper) was referred to as the tibial transverse axis (TTAx) in analogy with the femur. (Fig 2) The cadaver specimens were moved from full extension to 90° of flexion, while the optical stereotactic reference frames were followed by five previously calibrated infrared camera's (Vicon Motion Systems®, Los Angeles, USA). As the stereotactic optical frames are rigidly attached to the femur and the tibia, and their spatial relation to the important reference points and axes on the bones was documented by the CT scan, the position of all points and axes on the femur relative to the tibia can be computed.

The projection of FTAx and TTAx on the horizontal plane was performed with the specimens in full extension. (Fig 3) The relation between the tibial mechanical axis and the aforementioned femoral axes was computed with the knees in 90° of flexion (Fig 4).

Statistics: all datasets were checked for normal distribution. Pairwise comparisons between the different axes were performed in Statistica®, using student's T test. Correlations were evaluated using Pearson correlation.

RESULTS

1. Intra- and inter-observer variability

The results of the repeatability analysis are shown in Table I.

2. Variability and discrimination of the surface derived axes

The resulting angles between the projections on the horizontal plane of the four major rotational axes and the FTAx per specimen are displayed in table II. The surgical TEA is almost parallel to FTAx with a relative external rotation of 0,21°. The anatomical TEA has a mean external rotation relative to FTAx of 3,40°. The posterior condylar line has a relative *interna*l rotation of 1,41°. The perpendicular to the trochlear axis has a mean external rotation of 1,39°.

The angle between the PCL and the FTAx has the least variability with a standard deviation of 0,77° (range -2,96°/ -0,28°). The highest variability is found in the angle between the perpendicular to TRAx and the FTAx with a standard deviation of 6,12° (range -10,62° /+11,62°).

The PCL, the surg TEA and the anat TEA display a crisp discrimination, with p-values<0,005 for PCL/Anat TEA and Anat TEA/Surg TEA and p-values=0,008 for PCL/Surg TEA. The perpendicular to TRAx is non-discriminative from the other axes because of the high standard deviation (TRAx/PCL: p=0,0122, TRAx/Anat TEA = 0,251, TRAx/Surg TEA = 0,512) (Fig 5).

A strong correlation is found between the coronal alignment in full extension and the trochlear axis orientation: r = 0,81, p=0,001, indicating an increasing internal rotation of the TRAx orientation with increasing valgus (Fig 6) . A weak correlation was found with the Posterior Condylar Line orientation (r=0,36, p=0,257) and no correlation with Surgical or anatomical TEA.

3. Angle between the projected FTAx and TTAx at full extension

The projected centre of the medial condyle on the horizontal plane is found on average 1,6 mm (range -2,6 mm;-5,9 mm, std 3,84 mm) anterior of the tibial transverse axis, versus 2,83 (range -6,1 mm; -0,66 mm, std 3,04 mm) posterior for the projected centre of the lateral femoral condyle. This results in a mean angle between the FTAx and TTAx of 0,8° (range -1,8°; 3°, std 2,05°)(Fig 3)

4. Relation between the femoral axes and the tibial mechanical axis at 90° of flexion

For the analysis of the tibiofemoral alignment in relation with the distal femoral geometry, the angle between the tibial mechanical axis and the femoral rotation axes was computed. A graphical illustration is shown in fig 7 and the results are summarized in Table III.

The tibial mechanical axis is close to the perpendicular to the FTAx, Surg TEA and parallel to TRAx at 90° of flexion.

The TMA is at 2,17° of external rotation relative to the perpendicular of the PCL of the femur. As expected, based upon the distal femoral geometry values, the greatest variability is found in the angle between TMA and TRAx (Std 5,96, range -12,7/-6,86). There is significant difference at $p<0,005$ between FTAx/PCL, FTAx/Anat TEA, PCL/Anat TEA and Surg TEA/Anat TEA. Between FTAx, Surg TEA and TRAx there is no significant difference with p values $>0,05$.

DISCUSSION

One of the most important errors leading to revision in knee arthroplasty surgery is malalignment.[29] Where small errors might still be acceptable [5], the true outliers in alignment cause complications and failure. With respect to rotational malalignment of the femoral component, excessive internal rotation has been related to pain, stiffness and patellar instability [1-6,8]. In contrast, excessive external rotation has been related to flexion instabity [7], increased shear forces on the patella [9] and varus alignment in flexion [10].

Unfortunately, the surgical process of positioning the implant is subject to errors. Failure to align a component properly with a desired axis can be situated at three different levels. Sometimes, the desired axis is not visible in vivo (e.g. the femoral mechanical axis) and a secondary axis (e.g. the centre of the intramedullary canal) is chosen to serve as a guide during surgery. Ideally, this secondary axis has a reliable angular relation, in statistical terms small standard deviation, to the desired axis. A first level of error is the individual variability in the angular relation between the desired axis and the surgical secondary axis. The second level of error is related to the intra-operative determination of the secondary surgical axis, in other words, the ability of the surgeon to locate accurately and reproducibly anatomical landmarks that lead to the secondary surgical axis. Previous studies have emphasized the difficulties surgeons face in this area [30,31]. The third level of error is related to the positioning and fixation of the cutting block and the execution of the cut with the saw. The subject of this study is at the first level: the definition of the "desired axis" and its relation to the "secondary surgical axis".

The main weakness of this study is the small sample size, caused by the extensive technical set-up and time consumption of the experiment. On the other hand, the distribution of the coronal alignment of the specimens falls within the range of previously published cohorts [20], suggesting a representative sample.

We decided to compare the position of the proposed "desired" axis of the femur (FTAx) to the tibia, as a description of the rotation of the distal femur is intrinsically related to the tibia. In the extended knee, we hypothesized parallelism in the horizontal plane between the projected FTAx and TTAx . In the flexed knee at 90°, we hypothesized the tibial mechanical axis to be perpendicular to FTAx, resulting in neutral varus/valgus alignment.[10]

As shown in the results and graphically illustrated in fig 3, FTAx and TTAx virtually coincide as they are projected on the horizontal plane of the femur with the knee in extension. This is a strong indication that the TTAx, (called the anatomical tibial axis by Cobb et al) is a reliable landmark for describing rotation of the tibia and FTAx for the femur. In addition, at 90° of flexion, the extension of the tibial mechanical axis crosses the FTAx at a right angle, indicating neutral alignment. This is a second argument to accept this FTAx as a correct anatomical reference for describing the neutral rotation of the femur and guide the surgeon in the placement of the femoral component during TKA.

With this FTAx as a reference, the surface derived 'secondary surgical' axes can be examined. The results presented in Table I and Fig 5 indicate that the posterior condylar line, the anatomic transepicondylar axis and the surgical transepicondylar axis can be discriminated in the horizontal plane projection, based upon their different orientation amongst individuals. The posterior condylar line displays the smallest inter-individual variability with a standard deviation of less than one degree. It is internally rotated relative to the anatomic and surgical TEA. This is in line with previous published findings. [14-19,21,23]

Of the two transepicondylar axes, the horizontal plane projection the surgical TEA is almost parallel with the FTAx. The anatomical TEA is consistently more externally rotated than the surgical TEA (3,2°). This again confirms previously published work. [16,17,23]

Concerns can be raised about the trochlear axis. Despite the fact that the mean value of this axis shows an almost orthogonal orientation to the desired rotation axis (FTAx), the range (-10,6° to + 11,7°) is unacceptably high. The resulting standard deviation of 6,12° prevents a significant difference from the other axes. If used as a single reference for the femoral component, it would lead to unacceptable outliers in rotational alignment. In addition, a significant correlation was found between the amount of 'internal' rotation of the trochlear axis and the valgus alignment in the coronal plane, thereby seriously limiting the value of this reference in the valgus setting. This is in contrast with the original description of this trochlear axis by Arima et al. [19], where they proposed this axis for the knee with valgus deformity. However, in the referred study, the authors did not use valgus knees but 'thirty normal femora obtained from cadavera'. No further information on coronal alignment is given in this paper. The reported range of the angle between the PCL and TRAx is -1° to 10°.

In our study we found a range between PCL and TRAx of -7,66° to 11,95°. Three knees with valgus alignment form the lower end of this range. Siston et al also report the wide range of distribution of the TRAx in a recent paper. In a comparison between eleven orthopaedic surgeons using five alignment techniques for rotational alignment of the femoral component, this axis is reported as the most variable with a standard deviation of 7,6° and a range of -12° to 15°. [30]

What are the consequences of our results for surgical practice?

1. It is obvious that a common frame of reference is to be used if we want to discuss the achievement of optimal rotation of the femoral component. The definition of the femoral transverse axis as a geometrical reference can support future analysis of deformity in patients.

2. The values that we presented seem to strengthen previous reports that considered the surgical TEA as the closest surface derived axis to the desired alignment of the femoral component. However, this does not necessarily mean that surgeons should use this axis as a single reference for guidance of the rotational alignment of the femoral component. As stated earlier, this study only deals with the first level of error, being the individual variability in angular relationships. The second level of error, the inter- and intrasurgeon variability of finding the landmarks might be even more important, especially for the TEA, as the epicondyles are much harder to locate intra-operatively than on a 3D surface reconstruction. [31]

3. Given the individual variability in angular relationships, it seems logical to use the maximum information available in orienting the femoral component in the horizontal plane. There is no such thing as a reference line that will *always* guide the surgeon to a perfect position. One should also be aware that in the valgus knee, not only the posterior condylar line but also the trochlear AP axis tend to position the femoral component in internal rotation and should be used with great caution.

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FIG 1

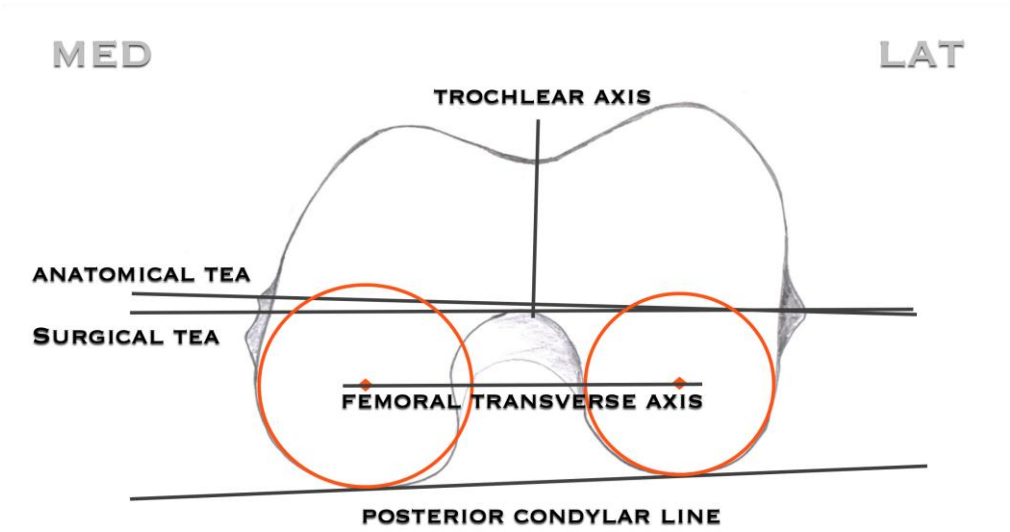

Fig 1. Display of the axes that have been studied in relation to the rotational alignment of the distal femur. The posterior tangent line is the tangent of the posterior part of the medial and lateral condyle. The anatomical transepicondylar axis connects the medial epicondyle to the lateral epicondyle. The surgical transepicondylar axis connects the medial sulcus to the lateral epicondyle. The trochlear axis connects the deepest point of the trochlea with the femur in caudal view to the highest point in the notch.

FIG 2

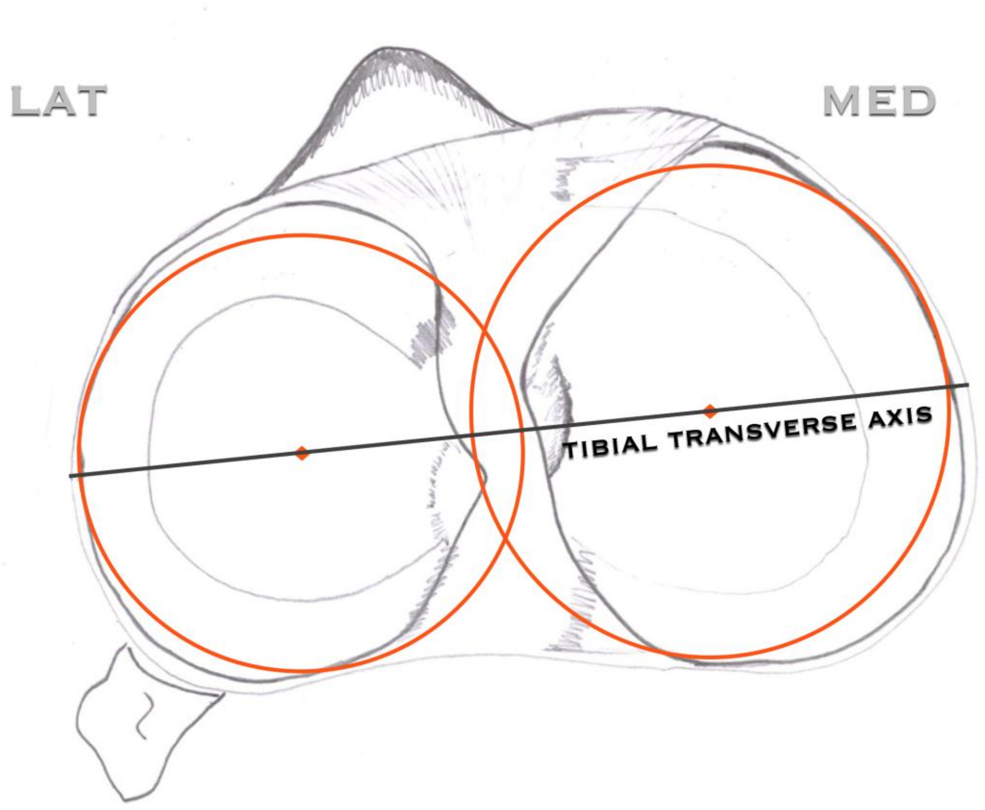

Fig 2: Graphical illustration of the definition of the tibial transverse axis, as defined by Cobb [25].

FIG 3

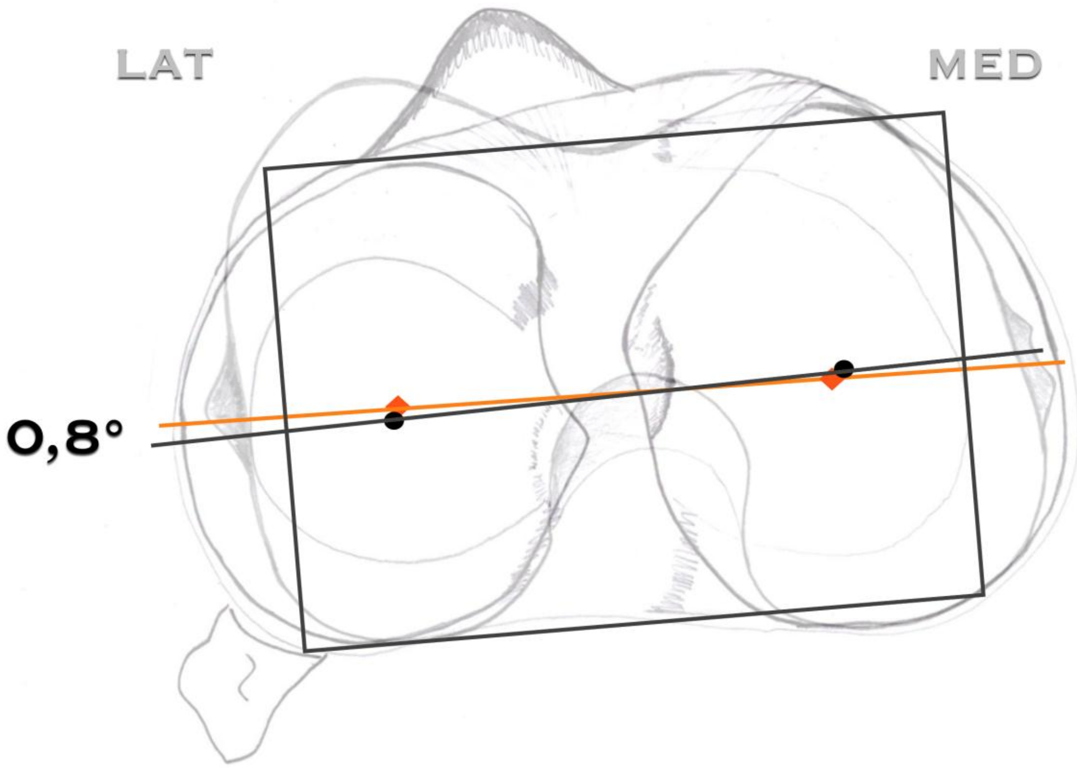

Fig 3: Illustration of the projection of the Tibial Transverse Axis (TTAx ◆) and the Femoral Transverse Axis (FTAx ●) on the horizontal plane of the femur. As shown, the projection of both axes in the extended knee virtually coincide.

FIG 4

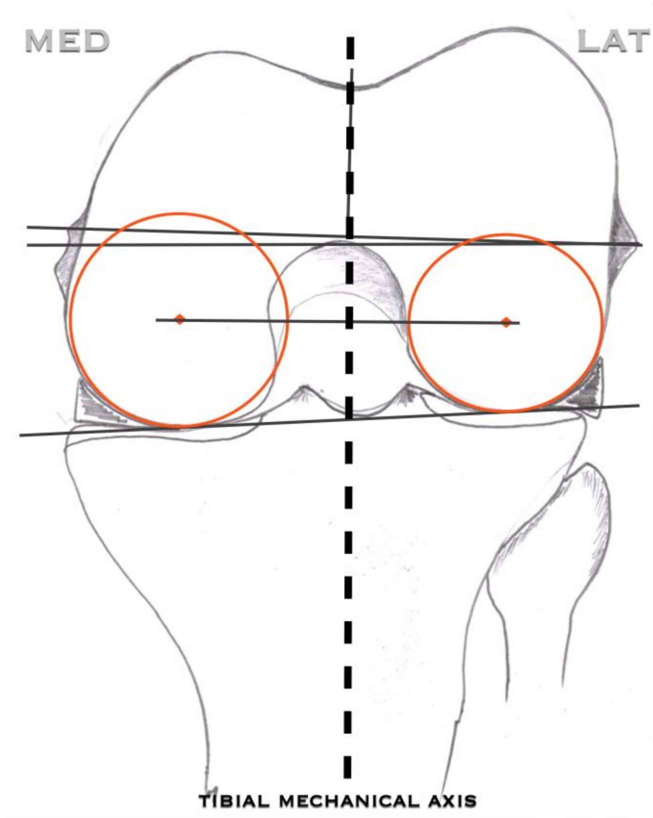

Fig 4. Relation between the tibial mechanical axis and the distal femur at 90° of flexion

FIG 5

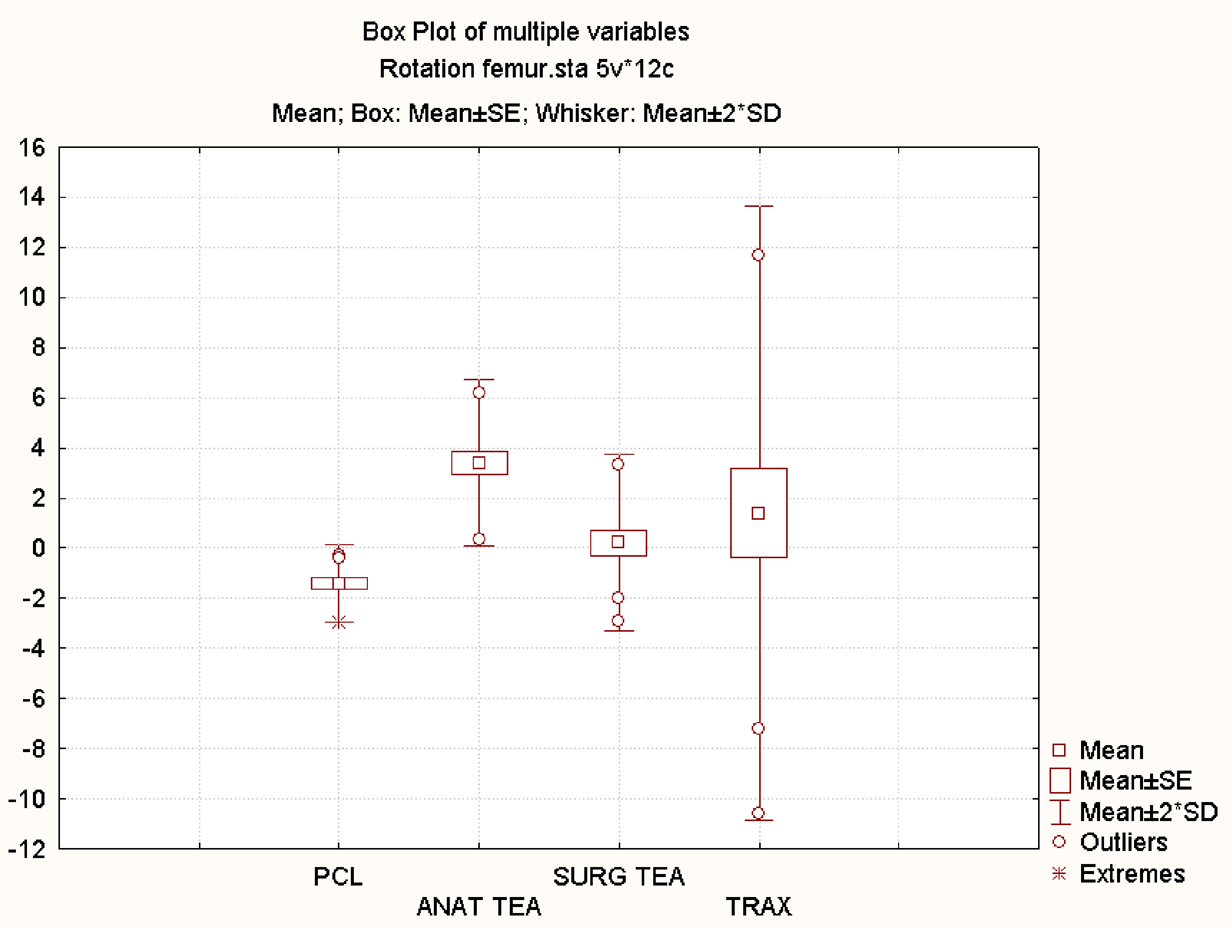

Fig 5: Box and Whisker plots of the four axes, clearly illustrating the small spread of the posterior condylar line, and the large inter-individual variability of the trochlear axis. Abbreviations: Posterior Condylar Line = PCL, Anatomic Transepicondylar Axis = Anat TEA, Surgical Transepicondylar axis = Surg TEA, Perpendicular to the Trochlear Axis =∞RAx

FIG 6

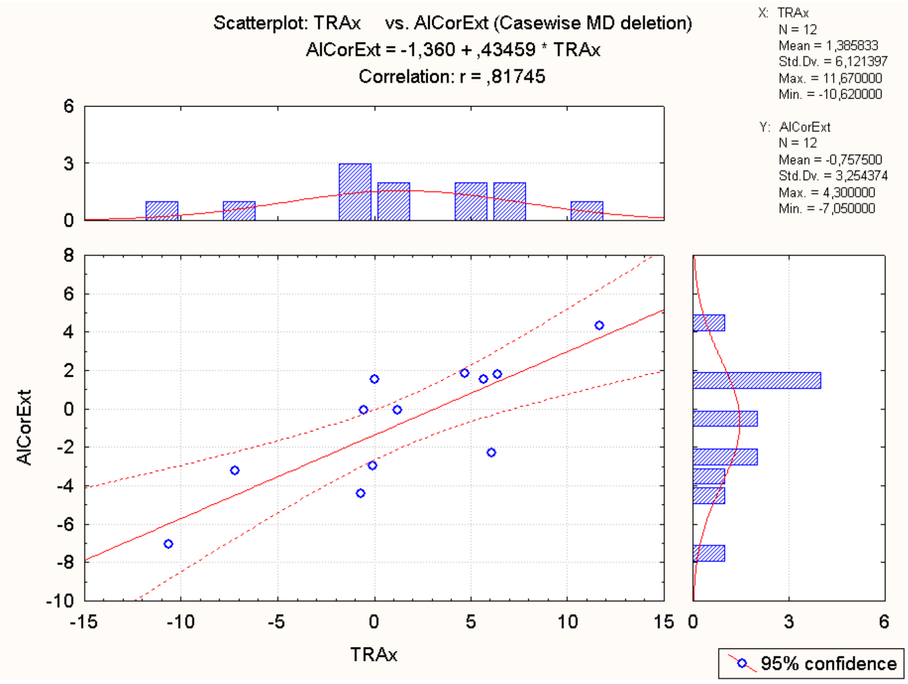

Fig 6. Correlation plot between coronal alignment in extension and the angle between the perpendicular to the trochlear axis (TRAx) and the Femoral Transverse Axis. As the coronal alignment goes in valgus, the perpendicular to TRAx shows a trend to internal rotation.

FIG 7

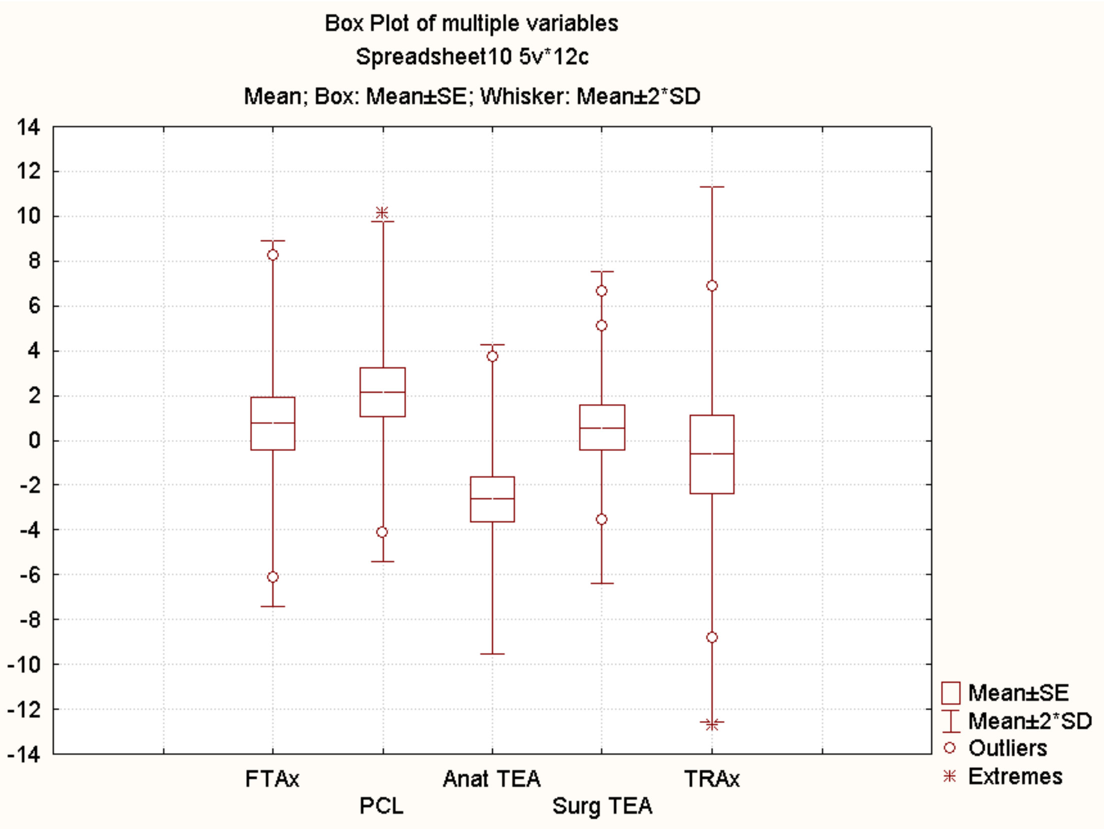

Fig 7: Alignment of the femoral axes relative to the tibial mechanical axis at 90° of flexion.

TABLE I

	Angle relative to FTAx in degrees				
	FTAx	PCL	Anat TEA	Surg TEA	∞TRAx
$\Delta\theta_{intra}$	1.15°	0.16°	0.52°	0.57°	1.24°
$\Delta\theta_{inter}$	1.15°	0.57°	1.15°	1.15°	2.07°

Table I**:** Intra- and interobserver angular deviation for the five femoral axes in degrees.

TABLE II

SPECIMEN	**PCL**	**Anat TEA**	**Surg TEA**	**∞ TRAx**
1	-0,28	3,44	1,10	-0,53
2	-1,23	4,44	1,52	1,23
3	-1,00	6,16	3,31	-0,06
4	-1,02	2,22	-1,73	4,69
5	-2,96	1,73	0,95	-7,21
6	-1,18	5,23	-0,76	-0,71
7	-0,39	3,21	0,42	5,65
8	-2,01	0,35	-2,91	0,03
9	-2,22	1,86	-2,00	-10,62
10	-1,44	3,26	0,81	6,08
11	-1,93	4,54	1,59	6,41
12	-1,22	4,34	0,24	11,67
MIN	*-2,96*	*0,35*	*-2,91*	*-10,62*
MAX	*-0,28*	*6,16*	*3,31*	*11,67*
MEAN	***-1,41***	***3,40***	***0,21***	***1,39***
STD	*0,77*	*1,66*	*1,77*	*6,12*

Table II. Angles formed between the four major rotational axes of the distal femur and the femoral transverse axis (FTAx), including minimum (min), maximum (max), means and standard deviations (std). Mean values are highlighted in bold. Negative values indicate a relative internal rotation of the variable in relation to FTAx, positive values a relative external rotation of the variable to FTAx. The mean values on the grey background illustrate significant difference p<0,005. Abbreviations: Posterior Condylar Line = PCL, Anatomic Transepicondylar Axis = Anat TEA, Surgical Transepicondylar axis = Surg TEA, Perpendicular to the Trochlear Axis =∞ TRAx .

TABLE III

SPECIMEN	**∞ FTAx**	**∞ PCL**	**∞ anat TEA**	**∞ surg TEA**	**TRAx**
1	3,96	4,24	0,52	2,86	4,49
2	4,48	5,71	0,04	2,96	3,25
3	1,12	2,12	-5,04	-2,19	1,18
4	3,37	4,39	1,15	5,10	-1,32
5	-2,01	0,95	-3,74	-2,96	5,20
6	0,55	1,73	-4,68	1,31	1,26
7	3,10	3,49	-0,11	2,68	-2,55
8	-6,11	-4,10	-6,46	-3,20	-6,14
9	-3,76	-1,54	-5,62	-1,76	6,86
10	-2,72	-1,28	-5,98	-3,53	-8,80
11	8,24	10,17	3,70	6,65	1,83
12	-1,03	0,19	-5,37	-1,27	-12,70

MIN	-6,11	-4,10	-6,46	-3,53	-12,70
MAX	4,48	10,17	3,70	6,65	6,86
MEAN	***0,20***	***2,17***	***-2,63***	***0,55***	***-0,62***
STD	3,66	3,79	3,46	3,48	5,96

Table III. Angles formed between the tibial mechanical axis on one hand and TRAx , the perpendiculars to FTAx, PCL, anat TEA, and surg TEA, including minimum (min), maximum (max), means and standard deviations (std). Mean values are highlighted in bold.. Negative values indicate a relative internal rotation of the variable in relation to TMAx, positive values a relative external rotation of the variable to TMAx. There is significant difference at $p<0,005$ between FTAx/PCL, FTAx/Anat TEA, PCL/Anat TEA and Surg TEA/Anat TEA. Between FTAx, Surg TEA and TRAx there is no significant difference with p values >0,05.