DOES TOTAL KNEE REPLACEMENT MODIFY FLEXION AXIS OF THE KNEE ON FRONTAL AND AXIAL PLANE REGARDLESS FROM LIMB ALIGNMENT?

D. BRUNI[1], L. BRAGONZONI[2], M. BONTEMPI[3], F. IACONO[1], M.P.NERI[1], S. BIGNOZZI[4], S. ZAFFAGNINI[1] and M. MARCACCI[5,6]

[1]2nd Orthopaedics and Traumatologic Clinic, Rizzoli Orthopaedic Institute, , Bologna, Italy; [2]Biomedical and Neuromotor Sciences - DIBINEM - The Alma Mater Studiorum, University of Bologna, Italy; [3]Biomechanics Laboratory, Codivilla-Putti Research Center, Bologna, Italy; [4]Orthokey Italia Srl, Italy; [5]Director of the 2nd Orthopaedics and Traumatologic Clinic, Rizzoli Orthopaedic Institute, Bologna, Italy; [6]Director of Biomechanics and Technologic Innovation Laboratory and Nanobiotechnology Laboratory, Codivilla-Putti Research Center, Bologna University, Bologna, Italy

The optimal reference for rotational positioning of femoral component in total knee replacement (TKR) is debated. Navigation has been suggested for intra-op acquisition of patient's specific kinematics and functional flexion axis (FFA). To prospectively investigate whether pre-operative FFA in patients with osteoarthritis (OA) and varus alignment changes after TKR and whether a correlation exists between post-op FFA and pre-op alignment. A navigated TKR was performed in 108 patients using a specific software to acquire passive joint kinematics before and after TKR. The knee was cycled through three passive range of motions (PROM), from 0° to 120°. FFA was computed using the mean helical axis algorithm. The angle between FFA and surgical TEA was determined on frontal (α^f) and axial (α^a) plane. The pre- and post-op hip-knee-ankle angle (HKA) was determined. RESULTS: Post-op FFA was different from pre-op FFA only on frontal plane. No significant difference was found on axial plane. No correlation was found between HKA-pre and α^A-pre. A significant correlation was found between HKA-pre and α^F–pre. The study concluded that TKR modifies FFA only on frontal plane. No difference was found on axial plane. Pre-op FFA is in a more varus position respect to TEA. The position of FFA on frontal plane is dependent on limb alignment. TKR modifies the position of FFA only on frontal plane. The position of FFA on axial plane is not dependent on the amount of varus deformity and is not influenced by TKR. Level of evidence, IV, case series.

Rotational alignment of the femoral component is fundamental to obtain a correct tibio-femoral (TF) and patello-femoral (PF) kinematics after total knee replacement (TKR) (1-4). Malrotation of the femoral component reduces implant survivorship and impairs functional results (1). Many reference systems and anatomical landmarks have been suggested to improve accuracy in the positioning of components but they demonstrated to have a low repeatability and a high intra- and inter-observer variability (3, 5-8). Therefore, the optimal surgical references to optimize rotational positioning of the femoral component during a TKR are still debated.

Navigation has been suggested to improve accuracy of implant positioning and to reduce the number of outliers in frontal and axial alignment (9-12). In any case, the accuracy in the acquisition of the anatomic landmarks used to plan implant

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Mailing address: Danilo Bruni, MD,
2nd Orthopaedics and Traumatologic Clinic,
Rizzoli Orthopaedic Institute,
Via Pupilli 1, 40136, Bologna, Italy
Tel.:+39 051 6366506
Fax: +39 051 583789;
e-mail address: d.bruni@biomec.ior.it; drdanilobruni@gmail.com

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positioning depends on the surgeon's experience (13-14). Furthermore, the use of navigation in TKR has failed to provide superior clinical results and implant survivorship compared to conventional procedures (15-16).

Despite these limitations, navigation has been recently used for intra-operative acquisition of the patient's specific kinematics and to describe the individual functional flexion axis (FFA) according to different mathematical algorithms (17). Its reliability in determining femoral component rotation in a TKR has been demonstrated in a cadaveric model (17) but not *in vivo*. Moreover, no data is reported in literature regarding FFA modification after a TKR compared to pre-operative condition, nor does a correlation exist between pre-operative limb alignment and post-operative FFA.

The main purpose of the present study was to prospectively investigate whether pre-operative FFA of the knee in patients with end-stage osteoarthritis (OA) and varus alignment changes after TKR. The secondary purpose was to determine whether a correlation exists between post-operative FFA and the amount of pre-operative varus deformity.

MATERIALS AND METHODS

A unilateral cruciate-retaining (CR), mobile-bearing (MB) TKR (Gemini-Light, Waldemar Link, Hamburg, Germany) was performed in a series of 108 consecutive patients with primary knee osteoarthritis (OA) and a Kellgren/Lawrence (K/L) (18) score of at least 4 points in the Authors' institution between 2008 and 2010. The study was approved by the Institutional Review Board and all patients provided their informed consent before surgery.

Demographics and pre-operative radiographic evaluation of limb alignment are resumed on Table I.

Preoperatively, all patients had weight-bearing antero-posterior (AP) and latero-lateral (LL) long film radiographs (19). We assumed a hip-knee-ankle angle (HKA) greater than 180° to be a valgus knee and a HKA less than 180° a varus knee (20). Twelve patients with valgus alignment were excluded from the study to avoid data dispersion due to the non-normal distribution of limb-alignment in patients with OA and because of kinematics abnormalities in patients with valgus knees (21-25).

Acquisition protocol

A surgical navigation system (BLU-IGS, Orthokey, Lewes, Delaware) (26) and a specific software (KLEE, Orthokey, Lewes, Delaware) (27) were used to acquire anatomical landmarks and passive joint kinematics (28). Anatomical and kinematic data were collected by the two Senior Authors after medial parapatellar arthrotomy before anterior cruciate ligament (ACL) and meniscal removal and after cementing final implant. Data were analyzed off-line using the Matlab software (Mathworks, Natick, MA, USA). The joint coordinate reference system (JCS) was defined according to Cole et al. (29) and Grood and Suntay (30). Anatomical landmarks acquired during the procedure are shown on Fig. 1. The functional hip joint centre (HJC) was identified through a pivoting motion, as described by Siston et al. (31).

For the femoral anatomical reference system, the proximal-distal (PD) axis was defined with the femoral mechanical axis (32) i.e., the line connecting HJC and the deepest point in the femoral notch (FN), as defined by Bertin (33). The medial-lateral (ML) axis was defined as the surgical transepicondylar axis (TEA) i.e., the line connecting the medial sulcus of the medial epicondyle (FME) and the lateral epicondyle (FLE), defined as the most lateral prominence of the lateral femoral condyle (6-7). The cross product between the PD- and ML-axis was defined as the anterior-posterior (AP) axis (Fig. 1).

For the tibial anatomical reference system, the PD axis was defined as the tibial mechanical axis i.e., the

Table I. *Demographics and pre-operative alignment.*

VARIABLE	VALUE
Sex (M/F)	42/66
Age* (years)	71 ± 4 (62-84)
Limb (right/left)	48/60
BMI* (kg/m2)	29 ± 3 (26-37)
HKA-pre*	174.7° ± 3.4° (168.1°-178.2°)

M: *male;* ***F***: *female;* ***BMI***: *body mass Index;* ***HKA-pre***: *preoperative hip-knee-ankle angle;* ***HKA-post***: *post-operative hip-knee-ankle angle;* *****:*values are expressed as mean±SD with range in brackets.*

line connecting the tibial spine point (TS) and the point equidistant between the medial (MM) and the lateral (LM) malleoli. The AP-axis was defined as the projection of tibial tuberosity point (TT) to the PD-axis, and the ML-axis, as the cross product between PD-axis and ML-axis (28) (Fig. 1).

FFA acquisition

The knee was cycled through three complete passive range of motions (PROM), from full extension to 120° of flexion and back to full extension, before and after implant positioning.

For each patient, the pre-operative FFA acquisition was performed after medial parapatellar arthrotomy, with intact menisci and ACL, using a temporary suture repair to reduce the patella in its anatomical position. In all acquisitions, the movement was performed while maintaining the femur elevated with one hand and holding the foot in neutral position with the other hand, without superimposing any additional load (26, 28).

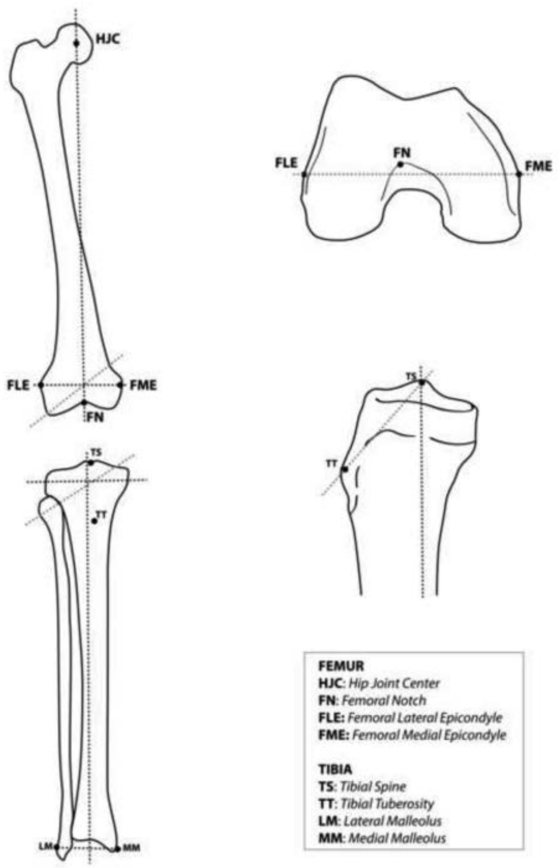

Fig. 1. *Anatomical landmarks acquired and joint coordinate reference system with femoral and tibial PD, ML and AP axis.*

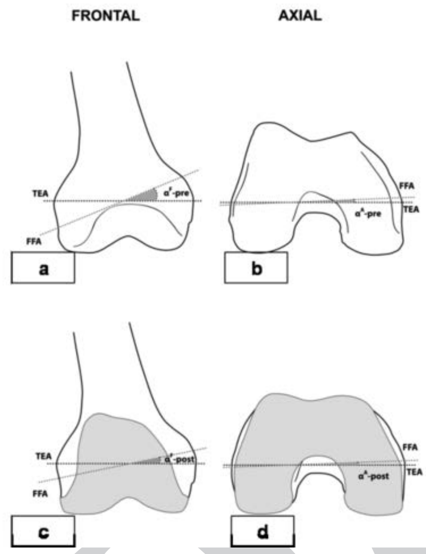

FIG. 2. ***a, b****): The angle between FFA and surgical TEA on frontal and axial plane before TKR implantation;* ***c, d****): illustrates the angle between FFA and surgical TEA after final implant positioning; The drawing illustrates a significant modification of FFA position with respect to TEA only on frontal plane and underlines that pre-operative FFA is in a more varus position respect to TEA.*

The FFA was computed using the mean helical axis algorithm (34). The angle between FFA and surgical TEA was determined on frontal (α^F-pre) and axial (α^A-pre) plane (Fig. 2).

Navigation was used to determine implant positioning. Femoral component rotational positioning was determined averaging Whiteside line and surgical TEA (4, 5) without considering PCA. After final implant positioning and capsular closure, post-operative FFA acquisition was performed, repeating the same movement and FFA was again computed. The angle between FFA and surgical TEA was again determined on frontal (α^F-post) and axial (α^A-post) plane (Fig. 2).

A varus position of FFA, with respect to surgical TEA in the frontal plane, was assigned a negative value, while a valgus alignment of FFA to TEA was assigned a positive valgus. For axial plane, we assumed negative values to describe a more internally rotated position of FFA with respect to surgical TEA, while more externally rotated position of FFA with respect to surgical TEA was assigned positive values (Fig. 2).

Data Analysis

The Grood and Suntay algorithm (30) was used to decompose instantaneous rotations and displacements, in order to describe the relative motion of the tibial

Table II. *Pre-operative and post-operative angles between FFA and TEA on frontal and axial plane and limb alignment.*

VARIABLE	PRE-OP	POST-OP	Δ	p	COMMENT
αF#	-3.9° ± 5.9°	-0.7° ± 5.8°	3.2° ± 11.7°	**<0.0001**	**REDUCTION OF VARUS POSITION RESPECT TO TEA ON FRONTAL PLANE**
αA#	0.8° ± 5.6°	0.0° ± 4.6°	0.8° ± 10.2°	0.0539	NOT SIGNIFICANT INCREASED INTERNAL ROTATION RESPECT TO TEA ON AXIAL PLANE
HKA*	174.7° ± 3.4° (168.1°-178.2°)	179.3° ± 2.4° (178.9°-184.5°)	4.6° ± 5.8°	**<0.0001**	**REDUCTION OF VARUS ALIGNMENT TO HAVE A NEUTRAL MECHANICAL ALIGNMENT OF TKR**

Pre-op*: pre-operative;* ***Post-op****: post-operative;* ***Δ****: variation;* ***p****: significancy;* ***αF****: angle between functional flexion axis and surgical transepicondylar line on frontal plane;* ***αA****: angle between functional flexion axis and surgical transepicondylar line on axial plane;* ***HKA****: hip-knee-ankle angle;* **#***: values are expressed as mean±SD;* ******: values are expressed as mean±SD with range in parentheses.*

frame with respect to the femoral one. Knee kinematics during PROM were described by computing the means of instantaneous flexion–extension (FE), internal-external (IE) and varus–valgus (VV) rotations as the cardian decomposition in the JCS.

Starting from the instantaneous helical axes (IHA), elaborated for each PROM using the least square approach (35), the mean helical axis (MHA) was computed and defined as the functional flexion axis (FFA) (34).

Statistical analysis

Descriptive statistical analysis was performed to evaluate data distribution both on pre- and post-implant values. Angles were described by means and standard deviations. The paired Student's *t*-test was performed to investigate whether a correlation exists between α^F-pre and α^F-post and between α^A-pre and α^A-post. The Pearson correlation was used to test if a relationship exists between α^F and α^A, before and after implant positioning, and pre-operative limb alignment determined with the HKA angle. Statistical significance was set to 95% (P=0.05) for all the tests.

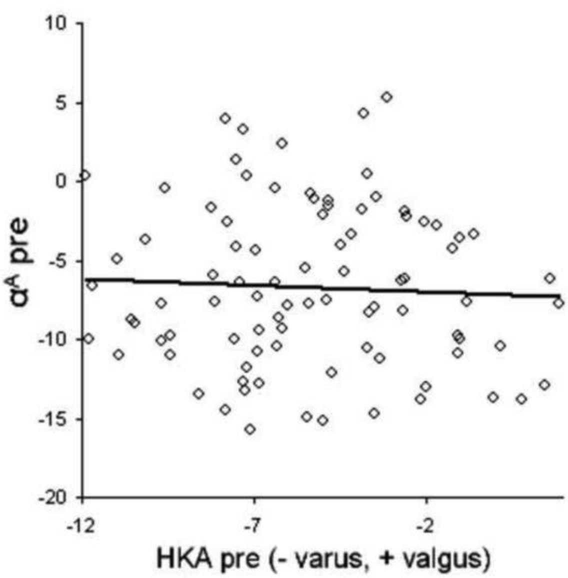

Fig. 3. *Chart shows no correlation between pre-operative limb alignment and preoperative FFA on axial plane.*

RESULTS

The post-operative FFA after TKR was different from the pre-operative FFA only on frontal plane. No significant difference was found between pre-operative FFA and post-operative FFA on axial plane in a 0° to 120° PROM (Tab. II). The angle between pre-operative FFA and surgical TEA was -3.9°±5.9° on frontal plane (α^F-pre) and 0.8°±5.6° on axial plane (α^A-pre) (Fig. 2, Table II).

No correlation was found between HKA-pre and α^A-pre (Fig. 3; Tab. III), while a significant correlation was found between HKA-pre and α^F–pre

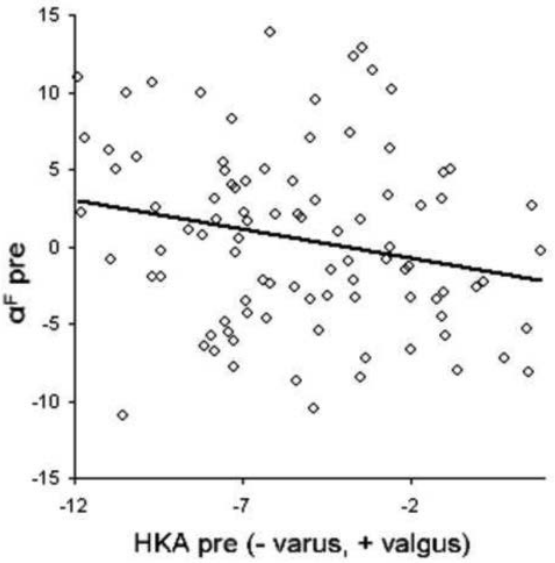

Fig. 4. *Chart showing a linear correlation between limb alignment and pre-operative FFA on frontal plane.*

(Fig. 4; Tab. III).

The value of α^F-post was -0.7°±5.8° and the value of α^A-post was 0°±4.6° (Table II, III). No correlation was found between HKA-pre and α^F-post or α^A-post (Tab. III). Pre- and post-operative values of limb alignment are reported on Table II.

DISCUSSION

The optimal surgical reference to optimize rotational positioning of the femoral component during a TKR is still debated. Navigation has been suggested to improve accuracy of implant positioning and to reduce the number of outliers in frontal and axial alignment (9-12).

Nevertheless, previous studies (17, 36) have demonstrated poor reproducibility of navigation when the TEA is used as a reference to set femoral component rotation. Conversely, other reports (13, 27) have demonstrated that TEA remains the gold standard among anatomical landmarks.

Recently, kinematically derived knee flexion axis has been suggested as a more reproducible and reliable reference to optimize femoral component positioning in TKR (17, 37-39) over conventional anatomical references. To the best of our knowledge, no study has demonstrated a correlation between kinematically derived FFA and conventional surgical TEA reference in navigated TKR. Therefore, the purpose of the present study was to investigate whether pre-operative FFA of the knee in patients with end-stage OA and varus alignment changes after TKR. The secondary purpose was to determine whether a correlation exists between pre- and post-operative FFA and the amount of pre-operative varus deformity.

Our study has several limitations. 1): valgus

Table III. *Correlation of αF-pre, αF-post, αA-pre and α-A-post with pre-operative alignment.*

VARIABLE	VALUE	HKA PRE-OP*	p	COMMENT
αF-pre#	-3.9° ±5.9°		**0.0445**	**PRE-OPERATIVE FFA POSITION ON FRONTAL PLANE IS MORE VARUS RESPECT TO TEA IN PATIENTS WITH HIGHER VARUS ALIGNMENT**
αA-pre#	0.8° ±5.6°	174.7° ± 3.4° (168.1°-178.2°)	0.9825	PRE-OPERATIVE FFA POSITION ON AXIAL PLANE NOTINFLUENCED BY AMOUNT OF VARUS DEFORMITY
αF-post#	-0.7° ±5.8		0.9698	POST-OPERATIVE FFA POSITION ON FRONTAL AND AXIAL PLANE NOT INFLUENCED BY AMOUNT OF VARUS DEFORMITY
α-A-post#	0° ± 4.6°		0.9472	

***HKA PRE-OP**: pre-operative hip-knee-ankle angle; **p**: variation; **αF-pre**: preoperative angle between functional flexion axis and surgical transepicondylar line on frontal plane; **αA-pre**: pre-operative angle between functional flexion axis and surgical transepicondylar line on axial plane; **αF-post**: post-operative angle between functional flexion axis and surgical transepicondylar line on frontal plane; **αA-post**: post-operative angle between functional flexion axis and surgical transepicondylar line on axial plane; #: values are expressed as mean ± SD; *: values are expressed as mean ± SD with range in parentheses.*

patients were not included. As suggested by Akagi et al. (40), in valgus knees a hypoplasia of the lateral condyle exists and modifies the femoral rotation throughout the ROM. Further investigation is going on to have a sufficient sample size of patients with primary OA and pre-operative valgus deformity; 2): FFA position was referred to the position of the surgical TEA on both frontal and axial plane. No CT scan was used to confirm surgical TEA position with respect to anatomical and ct-TEA. The comparison between surgical, anatomical and CT-TEA was not a purpose of the present study. Nevertheless, surgical TEA is widely accepted as gold standard for intra-operative rotational positioning of the femoral component with a non minimally-invasive approach, with good direct visualization of the epicondyles (7, 25, 41-45); 3): no comparison was performed with other anatomical landmarks used for rotational positioning of the femoral component during TKR i.e., the posterior condylar axis (PCA), the Whiteside's Line (5) and the anterior trochlear line (4, 46). Further investigation is needed to compare FFA with different rotational landmarks for femoral component positioning; 4): no comparison between different prosthetic designs was performed. Using a posterior stabilized (PS) design or a fixed bearing implant could have lead to different results; 5): pre-operative FFA acquisition was performed after medial parapatellar capsulotomy. Oussedik et al. (39) and Doro et al. (17) have already demonstrated that FFA is not influenced by this surgical exposure. Further investigation is needed to underline a possible contribution of capsule on FFA of the native knee; 6): no comparative study with an age matched control group with normal knees was performed. This is an intrinsic limitation of using a navigation system requiring rigid pins fixed to the bone. Colle et al. (37) have previously demonstrated that OA affects knee kinematics only on frontal plane comparing OA patients with an ACLR control group, that can be assumed to have a kinematic similar to a normal knee (47-49).

The present study supports these findings, since a difference between pre- and post-operative FFA was demonstrated only on frontal plane.

Considering three dimensional lower limb alignment also on sagittal and axial plane could have lead to different results. As already underlined by Oussedik et al (39), kinematically determined FFA could be influenced by tourniquet use and absence of active muscle contraction in the patient under anaesthesia. Further investigation is needed to evaluate the contribution of active muscle contraction to knee kinematics.

We did not analyse different flexion ranges separately, where the knee joint could present different motion patterns, i.e. the "screw-home" mechanism (50-52). Siston et al. (53) previously found a reduced screw-home motion in TKA patients respect to the pre-operative OA knees and an abnormal varus-valgus rotation in early flexion using a PS design. Further data analysis could reveal if different flexion ranges require different finite helical axis to describe the relative motion of the femur and the tibial.

Ligament release was not quantified and final FFA acquisition was performed after that ligament balancing was considered optimal by the operating surgeon.

Despite these limitations, to the best of our knowledge, the present study is the first report to demonstrate *in vivo* that TKR modifies FFA in patients with end stage OA only on frontal plane, while no difference was found between pre- and post-operative FFA on axial plane.

The angle between pre-operative FFA and TEA was -3.9°±5.9°, underlining that pre-operative FFA is in a more varus position respect to TEA. Moreover, no correlation was found between HKA-pre and α^A-pre while a correlation was found between HKA-pre and α^F-pre. The present study does not confirm the findings of Asano et al. (6) who determined a fixed functional axis corresponding to the surgical TEA during a 0° to 90° flexion in 9 healthy knees using a biplanar image-matching technique. Knee OA has been defined an "extension-gap disease" by Repicci et al. (54, 55) to underline that cartilage and subchondral bone erosion are mainly present on the weight-bearing surface of the medial femoral condyle.

Post-operative FFA position on frontal plane may be influenced by this wear pattern and by neutral mechanical alignment of the implant. On axial plane, the absence of wear on the posterior aspect of the medial femoral condyle and its circular shape are not altered by femoral component implantation. Whether a complete restoration of a neutral mechanical alignment is the optimal solution is a matter of debate (56-61). Further investigation is needed to determine whether a kinematic alignment of current prosthetic designs (58) or different implants with asymmetrical surfaces for the medial and lateral condyles are viable options to improve TKR kinematics.

In conclusion, the present study has demonstrated that the position of FFA on frontal plane is dependent on limb alignment and that TKR modifies the position of FFA only on frontal plane. The position of FFA on axial plane is not dependent on the amount of varus deformity and is not influenced by TKR.

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