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Primary Knee

Three-Compartment Phenotype Concept of Total Knee Arthroplasty Alignment: Mismatch Between Distal Femoral, Posterior Femoral, and Tibial Joint Lines

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ABSTRACT

Background: The purpose of the study was to assess whether patients who have different coronal alignment variations (functional knee phenotypes [FKP]) have distinctly different rotational alignment variations to justify an extension of the FKP concept to include rotational alignment parameters. The goals of the study were to: (1) determine the frequency of bony congruence between the anterior, distal, posterior femoral, and proximal tibial joint lines by using the extended FKP concept; and (2) connect these findings to clinical practice by simulating the impact of different alignment concepts on the most common FKP.

Methods: The posterior condylar angle (PCA) and anterior trochlear angle (ATA) were measured in 265 knees without osteoarthritic (OA). The PCA measurements of 2,692 knees with OA were extracted from the database. The patients were categorized into phenotypes based on these parameters. A phenotype represents an alignment variation of either the posterior (= PCA) or anterior femoral joint line (= ATA) in the axial plane. Rotational phenotypes (i.e., combination of alignment variations of the anterior and posterior femoral joint lines) were linked with the coronal phenotypes of these patients. The effect of three alignment concepts (mechanical, restricted, and unrestricted kinematic) on the most common FKPs was assessed.

Results: The distribution of the five most common coronal phenotypes did not differ among rotational phenotypes. The ATA and PCA were aligned parallel in 14.3% of the non-OA population. Distal femoral joint line (femoral mechanical angle), proximal tibial joint line (tibial mechanical angle), and PCA were aligned parallel in 17.0 and 11.2% of the non-OA and OA populations, respectively. All four joint lines (femoral mechanical angle, tibial mechanical angle, PCA, and ATA) were aligned in 2.3% of the non-OA population.

Conclusions: It is crucial to emphasize that preoperative assessment of a patient's anatomy should include the anterior and posterior femoral joint lines. The extended FKP concept could aid in this assessment and help identify patients who are at risk of complications due to malalignment or those who are likely to benefit from a particular alignment concept.

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Total knee arthroplasty (TKA) component orientation markedly affects clinical outcomes and prosthesis survival [1–3]. Traditionally, aligning three joint lines (coronal distal femoral, coronal proximal tibial, and posterior femoral) perpendicular to the mechanical axis of the lower limb has been the goal (mechanical alignment [MA] concept) to achieve component congruency and optimal mechanical conditions [4]. Yet, many patients remain dissatisfied after TKA despite recent technological advances [5–8]. This dissatisfaction might be due to the inflexible nature of this approach, which failed to restore the highly variable joint gap geometry and individual knee laxity. Driven by this dissatisfaction and fostered by the functional knee phenotype (FKP) concept, the use of personalized realignment concepts has increased in recent years [9–12]. There is now a large body of evidence suggesting that TKA alignment should be adjusted to the patient's individual bony anatomy and soft tissue envelope [1,9,13,14]. It remains a topic of debate as to which concept or technique most accurately restores a patient's bony alignment when considering the patient's soft tissue envelope [6,15,16]. Interestingly, these concepts only focus on optimizing the orientation of the distal femoral and proximal tibial joint lines (e.g., the coronal alignment). The orientation of the posterior femoral joint line (e.g., femoral component rotation) is rarely discussed despite the decade-old debate regarding the optimal orientation of the posterior femoral joint line when using MA alignment. Meanwhile, the importance of rotational alignment of the femoral component for a well-functioning TKA is unquestionable. It is evident that not all of these factors can be influenced by the alignment strategy, and modifications specifically aimed at altering these parameters will inevitably result in alterations to other alignment parameters. However, the orientation of the anterior femoral joint line (anterior trochlear angle [ATA]) in the axial plane appears particularly interesting as it is directly accessible during surgery and is intrinsically linked to the orientation of the posterior femoral joint line (posterior condylar angle [PCA]) via femoral component rotation. Going one step further, variations in the shape and path of the trochlea as well as other anterior knee compartment parameters, such as anterior offsets, have been well studied but are rarely included in these alignment strategies [17–21]. Also, bony congruency, which is between the femoral and tibial joint lines as well as between femoral joint lines, has been neglected during this discussion. A thorough understanding of the orientation of all four joint lines (distal femoral joint line [femoral mechanical angle (FMA)], posterior femoral joint line [PCA], anterior femoral joint line [ATA], and proximal tibia joint line [tibial mechanical axis (TMA)]) and their relationship to each other seems to be of paramount clinical importance for achieving balanced extension (first compartment, proximal tibial, and distal femoral joint line) and flexion (second compartment, proximal tibia, and posterior femoral) gaps as well as a perfect patellar tracking (third compartment, orientation of the trochlea).

The orientation of these joint lines and their relationship to each other has been described by numerous studies, yet correlations appear to contradict the principles of personalized alignment where population-based relationships are less relevant than the patient's unique anatomy. The FKP concept is an alternative to this population-based approach. The concept is based on the assumption that there are certain combinations of joint line orientations, the so-called FKPs, which represent distinct alignment variations and, therefore, might benefit from a specific treatment (e.g., one variation might benefit from a certain alignment concept or implant) [9,13,22–24]. However, the concept has been limited to the coronal plane, and most recent studies have found no or only a weak correlation between the rotational and coronal alignment parameters. It must, therefore, be hypothesized that patients who have the same coronal alignment variation (e.g., coronal phenotypes) will have distinctly different rotational alignment variations (e.g., rotational phenotype), indicating the need to expand the FKP concept beyond the coronal alignment.

The aim of this study was threefold: first, to extend the FKP concept to include rotational alignment parameters and compare rotational phenotypes among the most common coronal phenotypes to test the abovementioned hypothesis; second, to determine the frequency of bony congruency between the anterior, distal, and posterior femoral and proximal tibial joint lines using the extended FKP concept and detect distinct alignment variations; and third, to connect these findings to clinical practice by simulating the impact of different alignment concepts on the most common FKP. A young non-osteoarthritic (non-OA) and osteoarthritic (OA) population were included to ensure that the possible differences would not only be observed in a population affected by OA and to include a large sample size.

Methods

Patient Populations—Non-OA Population

The non-OA population represents a subpopulation of a previously published population [9,22,23]. A detailed description of the data collection and coronal alignment of the population can be found elsewhere [9,13,22,23]. Briefly, the hospital archives of the cantonal hospital Baselland (Kantonsspital Baselland CH-4101 Bruderholz, Switzerland) were searched for patients aged < 45 years and > 16 years who received a computed tomography (CT) of the knee according to the Imperial Knee Protocol [25]. Each leg of these patients meeting the aforementioned criteria was assessed separately for the following exclusion criteria: hip, knee, or ankle prosthesis, osteotomy; any radiological signs of OA or fractures; and reported injury of the collateral ligaments. Patients were additionally excluded for this study if there was any note of patella-related symptoms (e.g., dislocations, feeling of instability, positive apprehension test) in their patient's letters, if their radiographs showed any form of deformity (e.g., trochlea dysplasia), or if there were any notes of a previous patella-related surgery (e.g., MPFL reconstruction). All patients underwent 99mTc-hydroxymethane diphosphonate single-photon emission computed tomography/CT of the knee according to the Imperial Knee Protocol using Symbia T16 (Siemens, Erlangen, Germany). The CT scans consisted of 3-mm-thick low-dose slices of the femoral head and ankle and high-resolution 0.7-mm slices of the knee. Both legs of 114 patients and a single leg of 37 patients were included in the study. A single-photon emission computed tomography/CT was conducted for the following reasons: knee pain of unknown origin (e.g., anterior knee pain without trauma; $n = 22$); osteochondritis dissecans ($n = 13$); and persistent pain after treatment of sports injury ($n = 87$).

A total of 265 non-OA knees were included (right side to left side ratio 133:132), of which 178 were from men and 87 were from women. The mean age in the non-OA group was 30 ± 6.6 SD (range, 16 to 44).

Patient Populations—OA Population

The OA population has also been previously described [13]. All CT scans collected from January 2017 to December 2019 in the Knee-PLAN 3D database (Symbios Orthopédie S.A., Yverdon-Les-Bains, Switzerland) were retrospectively evaluated. The CT scans in this database were collected by the manufacturer to enable the manufacturing of the company's personalized 3-dimensional printed TKA. The following exclusion criteria were applied: patients aged < 50 years and > 91 years at the time of imaging, evidence of previous trauma, previous osteotomy, signs of rheumatoid arthritis, and a flexion deficit of more than 15°. A total of 2,691 OA knees were evaluated (right side to left side ratio, 1,397:1,294), of which 1,075 were from men and 1,616 were from women. The mean patient age was 71 ± 8.5 SD (range, 50 to 90).

Alignment Parameters

The following alignment parameters were measured in the non-OA population: PCA and ATA. The PCA was defined as the angle between the surgical transepicondylar axis (sTEA) and the posterior condylar line. The sTEA was defined according to Berger et al., as the line connecting the sulcus of the medial epicondyle to the lateral epicondylar prominence [26]. The ATA was defined as the angle between the sTEA axis and the tangent to the anterior points of the lateral and medial trochlea femoris at the level where the trochlea groove is the deepest. Positive values indicate internal rotation of the condyles and trochlea, and negative values indicate external rotation. Figure 1 shows the measurement technique for these two angles. In the OA population, the ATA was not available because it was not routinely collected in the database; thus, our analysis was limited to PCA.

Additionally, the tibial mechanical angle (TMA), also known as the medial proximal tibia angle, and the FMA (which equals 180 minus the lateral distal femoral angle) of these patients were extracted from previously collected data [13,23,27]. Figure 2 illustrates the measurement techniques for these angles in detail. The TMA was measured as the medial angle between the mechanical axis of the tibia and a tangent to the proximal tibial joint line in the coronal plane. The FMA was measured as the medial angle between the femoral mechanical axis and tangent to the distal femoral condyle. An experienced engineer who had more than 10 years of experience in the field performed all parameter measurements using the validated planning software Knee-PLAN (Symbios), which has a reported accuracy of less than 1° [28].

FKP Concept—Phenotyping

The FKP concept is based on the assumption that there are certain combinations of joint line orientations, the so-called FKPs, which represent distinct alignment variations and, therefore, might benefit from a specific treatment (e.g., one variation might benefit from a certain alignment concept or implant). The original FKP concept is based on the alignment of a young non-OA population [9,22,23] and includes the orientation of the distal femoral joint line (FMA, femur phenotype), proximal tibial joint line (TMA, tibia phenotype), and the overall lower limb alignment (hip–knee–ankle angle). A phenotype represented an alignment variation of one of these parameters (the femoral joint line orientation based on FMA, tibial joint line orientation based on TMA). An alignment variation is defined as a 3° range (1.5° + 1.5) of one of these parameters. The mean values of these phenotypes represent 3° increments of the angle starting from the overall mean value of the angle found in the young non-OA population.

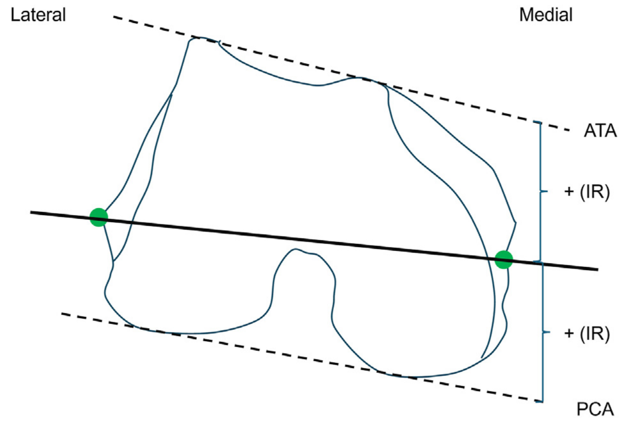

Figure 1. The posterior condylar angle (PCA) was defined as the angle between the surgical transepicondylar axis (sTEA) and the posterior condylar line. The anterior trochlear angle (ATA) was defined as the angle between the sTEA axis and a tangent to the anterior points of the lateral and medial trochlea femoris at a level where the trochlea groove is the deepest. Positive values indicate an internal rotation (IR) of the condyles/trochlea and negative values indicate an external rotation (ER). The sTEA was defined according to Berger et al., as the line connecting the sulcus of the medial epicondyle to the lateral epicondylar prominence [26].

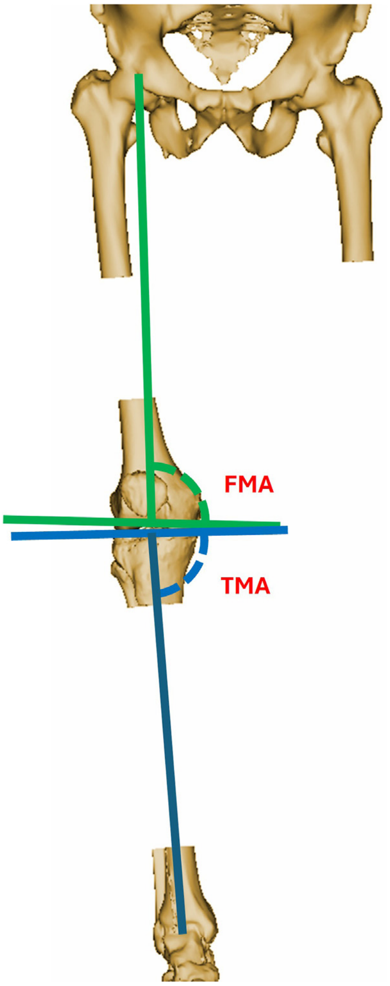

Figure 2. The tibial mechanical angle (TMA) was measured as the medial angle between the mechanical axis of the tibia and tangent to the proximal tibial joint line in the coronal plane. The femoral mechanical angle (FMA) was measured as the medial angle between the femoral mechanical axis and tangent to the distal femoral condyle.

This concept was extended by adding PCA and ATA to include information regarding the rotational alignment. The PCA was chosen because it is accessible during surgery without advanced technologies, can reliably be measured, and has an established impact on clinical outcomes. The ATA is defined by the prosthetic design and rotational alignment of the component (usually described using the PCA); therefore, it is not directly accessible during surgery. However, ATA was included since it was highly relevant to the patella tracking. There were three degrees of internal rotation relative to the sTEA chosen as neutral for the PCA and ATA to match the neutral phenotype of both the femur and

Table 1
Nomenclature for the Different Phenotypes.

Name	Joint Line A (Angle)	Joint Line B (Angle)
Extension phenotype[a]	Distal femoral joint line (FMA)	Proximal tibia joint line (TMA)
Flexion phenotype	Posterior femoral joint line (PCA)	Proximal tibia joint line (TMA)
Femur phenotype	Distal femoral joint line (FMA)	Posterior femoral joint line (PCA)
Rotation phenotype	Posterior femoral joint line (PCA)	Anterior trochlear angle (ATA)
Surgical phenotype	Distal femoral joint line (FMA; Joint line A) Proximal tibia joint line (TMA; Joint line B) Posterior femoral joint line (PCA; Joint line C)	

[a] These phenotypes have been reported in 2 previous studies (referred to as knee phenotypes) and will therefore not be reported in this study.

tibia. The range of each phenotype was set to 3° (±1.5° from the mean of the phenotype) to ensure compatibility with previously presented phenotypes for the coronal alignment. The nomenclature of phenotypes is structured as follows: the first part (NEU, IT, EXT) indicates the direction of alignment. The second subscript (PCA) denotes the measured angle. The last part (0, 3, 6, 9, and 12°) represents the mean deviation of the phenotype from the mean.

The overall lower limb alignment (usually measured as hip–knee–ankle angle) was excluded in this version due to evidence from two recent studies, suggesting that the amount of deviation from a neutral lower limb alignment is less important when aiming to restore the pre-arthritic alignment [13,29]. Furthermore, intraoperatively, the overall lower limb alignment cannot be assessed without advanced surgical instruments, and surgeons usually focus on flexion and extension gaps. The concept was adapted to consider these new findings, reduce complexity, and increase accessibility.

Combinations of phenotypes were built, and the distribution of the population among them was assessed. The nomenclature for the different combinations is presented in Table 1.

Alignment Concepts

The impact of three alignment concepts on the orientation of the different joint lines in the non-OA and OA populations was simulated. Table 2 lists the target for each angle of the different alignment concepts. For simplicity, the implementation of a prosthesis with parallel anterior and posterior femoral joint lines was assumed (e.g., PCA = ATA relative to sTEA).

This study was approved by the local ethical committee (EKNZ 2018-00223). All procedures were performed in accordance with the ethical standards of the institutional and/or national research committee and with the 1,964 Declaration of Helsinki and its later amendments or comparable ethical standards.

Results

Descriptive Statistics

Descriptive statistics, Pearson's correlations, and the strength of correlation are presented in Tables 3 and 4.

Rotational and Coronal Phenotypes

The frequencies of the posterior femoral joint line phenotypes (PCA) in the most common coronal phenotypes (FMA + TMA) in OA and non-OA knees are presented in Tables 5 and 6. The frequency of the anterior femoral joint line phenotypes (ATA) in the most common coronal phenotypes (FMA + TMA) in non-OA knees is presented in Table 6. Figure 3 illustrates the frequency of the anterior femoral joint line phenotypes in the most common surgical phenotypes (FMA + TMA + PCA). To increase readability the amount of rotation was not considered for this figure (internally rotated phenotypes (e.g., IR 3, IR 6, and IR 9, were summarized into one phenotype).

Part 2—Bony Joint Line Congruency

The PCA and FMA were oriented parallel in 43.2 and 37.1% of all non-OA and OA patients, respectively. Table 7 presents the distribution of non-OA and OA populations among the different femur phenotypes and rotational phenotypes.

The FMA, TMA, and PCA were aligned parallel in 17.0% of the non-OA population. They were 3° oblique (varus, valgus, and internally rotated) to the corresponding reference in 82.2% of all non-OA patients who had 3 parallel joint lines (FMA, TMA, and PCA) (14.0% of all non-OA patients). Table 8 presents the distribution of non-OA and OA populations among the surgical phenotypes.

Table 2
Definitions for the Different Alignment Concepts.

Alignment Concepts	Joint Lines		
	Distal Femoral (FMA)	Proximal Tibia (TMA)	Posterior Femoral (PCA)
Mechanical alignment (MA)	90°	90°	0° (relative to the sTEA, e.g., parallel to sTEA)
Anatomical alignment (AA)	93°	87°	3° IR (relative to the sTEA)
Restricted kinematic alignment (rKA)	No change[a] (FMA + TMA limited to 180° ± 3)	No change[a] (limited to 90° ± 5)	No change[a] (limited to 90° ± 5)
Kinematic alignment (KA)	No change	No change	No change

The MA aims to position the distal femoral joint line (FMA) and proximal tibia joint line (TMA) perpendicular to the mechanical axis of the corresponding bone, and to rotate the femoral component 3° externally (aiming for a PCA parallel to the surgical transepicondylar axis [sTEA, the line connecting the sulcus of the medial epicondyle to the lateral epicondylar prominence]) to match the orientation of the proximal tibial joint line. In the AA concept, all three joint lines are tilted/rotated 3° compared to the MA concept, mimicking the average native orientations of joint lines (e.g., 3° varus for the TMA, 3° valgus for the FMA, no change in PCA (=aiming for a 3° internally rotated PCA relative to the sTEA the kinematic alignment [KA] and the restricted kinematic alignment [rKA] aim to restore the pre-arthritic alignment of patients).

[a] The rKA thereby restricted the deviation of the joint line for the mechanical neutral to optimize prosthesis survival (FMA and TMA must be within 90° ± 5 and the sum [e.g., HKA] within 180° ± 3. PCA remains unchanged).

Table 3
Mean Values and SD for Anterior Trochlear Angle (ATA) and Posterior Condylar Angle (PCA) Separated by Sex and Group (Osteoarthritic [OA] Versus Non-OA).

Groups	Angle	Total		Men		Woman		*P*-Value
		Mean	SD	Mean	SD	Mean	SD	
Non-OA	PCA	92	1.8	92.1	1.8	91.8	1.7	n.s.
	ATA	6.2	3.3	6.1	3.2	6.3	3.7	n.s.
OA	PCA	92.1	1.9	91.9	1.9	92.2	1.9	<0.005

P values correspond to the comparison between genders.
n.s., not significant.

In 14.3% of the non-OA population, PCA and ATA were aligned parallel. They were both 3° internally rotated relative to the sTEA in 9.1%, 6° internally rotated in 2.3%, and 3° externally rotated in 2.6%.

The FMA, TMA, and PCA were aligned parallel in 11.2% of the OA population. They were 3° oblique (varus, valgus, and internally rotated) to the corresponding reference in 81.7% of all OA patients who had three (FMA, TMA, and PCA) parallel joint lines (9.14% of all OA patients). All four joint lines (FMA, TMA, PCA, and ATA) were aligned similarly in only 2.3% of the non-OA population.

Impact of Alignment Concepts

The impact of the three alignment concepts on joint line orientation in the five most common non-OA and OA populations is shown in Figures 4 through 6.

Discussion

The study has two major findings. Patients who had different coronal alignment variations (e.g., coronal phenotypes) have similar rotational alignment variations, and thus, the FKP concept should be extended to include rotational alignment parameters. These findings are in accordance with results from a recently published study using a different phenotype concept [30]. The impact of alignment strategies will thus differ significantly between patients who have the same coronal alignment. Also, based on this extended version of the FKP concept, it was shown that there is only a small percentage of individuals who have parallel-aligned posterior femoral, distal femoral, and proximal tibial joint lines. This number further decreased when considering the anterior femoral joint line. These findings are relevant because neither current alignment concepts nor off-the-shelf (OTS) implants take this divergence into account. On the one hand, they support the current trend that the orientation of the femoral and tibial components should be adapted to the individual anatomy and not only in the coronal but also in the axial plane. On the other hand, they highlighted the inherent limitations of the current OTS, which cannot be overcome by advanced alignment strategies. The so-called “third space” in TKA, compromising the patello-femoral joint, the extensor apparatus as well as the medial and lateral retinaculum, is poorly understood and challenging to manage intraoperatively [31]. A mismatch between the native or OA anatomy of the patellofemoral joint and current OTS is well documented, with neither the anterior offset [7,17,21], trochlear shape [32], medial-lateral, nor the orientation of the trochlear sulcus in the coronal plane being restored by current implant designs [17,19,33,34]. Some of these limitations might be related to the used alignment concept and might be overcome by using advanced implant alignment strategies [3,35], as was recently illustrated in an editorial by Bonnin et al. [36]. The orientation of the distal femoral joint line and the trochlear sulcus in the coronal plane are associated [37,38], and modern alignment concepts (kinematic and functional) have thus been found to better restore the native trochlear sulcus in the coronal plane [18,34,39,40]. However, the internal/external orientation of the trochlea itself is somewhat independent of the course of the trochlea sulcus and independent of the internal/external orientation of the posterior femoral joint line in the native and OA knee. This divergence between anterior femoral and posterior joint line orientation cannot be overcome by adapting the alignment strategy of the component because current implants place these 2 joint lines at a fixed angle [36]. As highlighted by previous studies, the orientation of the posterior condylar line is highly variable, and therefore, a predefined rotational alignment of the femoral component will result in a change in alignment and potential suboptimal outcomes [41–44]. Numerous methods have been proposed for the rotational alignment of the femoral component. However, no superior approach was found. In concept, rotational alignment should not be independent of coronal alignment. Yet, the correlation between rotational and coronal alignment is an area of debate, with some studies reporting a relationship between the two [42,45–47] whereas others have found no such correlation [30,48]. Our data showed no or only a weak correlation between the coronal and rotational alignment parameters. As mentioned above, defining alignment goals on population-based correlations between angles contradicts the principles of personalized alignment concepts. Furthermore, our simulations highlight that the impact of different concepts varies depending on the assessed plane and joint line. Considering the most common phenotypes in the non-OA population, femoral component rotation according to the MA concept would have re-established the patient’s anatomy (ATA and PCA) in 14.3% of all patients (NEU$_{\text{FMA}}$0° NEU$_{\text{TMA}}$0°ER$_{\text{PCA}}$3°, NEU$_{\text{FMA}}$0° VAL$_{\text{TMA}}$3°ER$_{\text{PCA}}$3°) but would have changed the coronal alignment in half of these patients (NEU$_{\text{FMA}}$0° NEU$_{\text{TMA}}$0°ER$_{\text{PCA}}$3°). Our findings align with prior research that focused on the MA concept. Blakeney et al. conducted simulations involving 1,000 TKA patients and assessed gap imbalances within two variations of the MA concept [49]. They noted no imbalances (medial-lateral or extension-flexion) in only 32% of valgus and 64% of varus patients when systematically adjusting the femoral component parallel to the sTEA. Similarly, Gu et al. explored 4 rotation methods for the femoral component within the MA approach [50]. Their findings revealed medial or lateral compartment instability in the medial and lateral aspects in 42 to 74% and 0 to 6% of the patients, respectively. Rivière et al. simulated two variations of the MA alignment concept and assessed collateral ligament imbalance [18]. They found an imbalance of 30 to 40% with the conventional concept but no imbalance with the experimental concepts. Niki et al. simulated an MA alignment in 60 patients and assessed imbalances as well as changes in the flexion–extension axis [51]. They reported a bony gap discrepancy between the flexion and extension gaps in 47% of the cases.

Table 4
Pearson's Correlations for Anterior Trochlear Angle (ATA) and Posterior Condylar Angle (PCA) Separated by Group (Osteoarthritic [OA] Versus Non-OA).

Angles	Non-OA			OA		
	Pearson’s r	*P*-Value	r^2	Pearson’s r	*P*-Value	r^2
FMA versus PCA	0.031	n.s.	0.001	0.131	<0.005	0.017
FMA versus ATA	0.059	n.s.	0.004			
TMA versus PCA	−0.169	n.s.	0.029	0.006	n.s.	0.000
TMA versus ATA	0.044	n.s.	0.002			
PCA versus ATA	0.344	<0.005	0.118			

FMA, femoral mechanical angle; TMA, tibial mechanical angle; n.s., not significant.

Going one step further by considering the anterior femoral joint line, surgeons appear to be in a dilemma because either the ”third space” or the flexion gap is compromised in the majority of patients who had current implant designs and alignment concepts. Differences in the orientation of the anterior (trochlea) and posterior femoral joint lines are well established in the literature, but the

Table 5

Frequency of the Posterior Femoral Joint Line Phenotypes (Posterior Condylar Angle [PCA]) in the Most Common Coronal Phenotypes (FMA + TMA) in Osteoarthritic (OA) Knees.

PCA	NEU$_{FMA}$0°NEU$_{TMA}$0°		NEU$_{FMA}$0°NEU$_{TMA}$0°		VAR$_{FMA}$3°NEU$_{TMA}$0°		VAR$_{FMA}$3°VAR$_{TMA}$3°		VAL$_{FMA}$3°NEU$_{TMA}$0°		Total	
	468	(%) 17.4	364	(%) 13.5	323	(%) 12.0	249	(%) 9.3	227	(%) 8.4	2,685	(%) 99.8[a]
IR 3	41	8.8	32	8.8	12	3.3	24	9.6	31	13.7	253	9.4
Neu	**246**	**52.6**	**201**	**55.2**	**169**	**52.3**	**139**	**55.8**	**123**	**54.2**	**1,406**	**52.2**
ER 3	171	36.5	118	32.4	130	35.7	81	32.5	68	30.0	946	35.2
ER 6	10	2.1	13	3.6	12	3.3	5	2.0	4	1.8	80	3.0

The bold indicated Neutra values.

NEU, neutral; VAR, varus; VAL, valgus; IR, internal rotation; ER, external rotation; FMA, femoral mechanical angle; TMA, tibial mechanical angle.

[a] Phenotypes representing less than 0.1% of the OA population are not shown.

Table 6

Frequency of the Posterior Femoral Joint Line Phenotypes (Posterior Condylar Angle [PCA]) and Anterior Femoral Joint Line Phenotypes (Anterior Trochlear Angle [ATA]) in the Most Common Coronal Phenotypes (FMA + TMA) in Nonosteoarthritic Knees.

PCA	NEU$_{FMA}$0°NEU$_{TMA}$0°		NEU$_{FMA}$0°VAL$_{TMA}$3°		VAL$_{FMA}$3°NEU$_{TMA}$0°		NEU$_{FMA}$0°VAR$_{TMA}$3°		VAL$_{FMA}$3°VAL$_{TMA}$3°		Total	
	65	24.5% (%)	48	18.1% (%)	27	10.2% (%)	25	9.4% (%)	21	7.9% (%)	$n = 265$ (%)	
IR 6	1	1.5	0	0.0	0	0.0	0	0.0	0	0.0	2	0.8
IR 3	5	7.7	2	4.2	2	7.4	0	0.0	2	9.5	18	6.8
NEU	**37**	**56.9**	**28**	**58.3**	**13**	**48.1**	**19**	**7.2**	**10**	**47.6**	**144**	**54.3**
ER 3	22	33.8	16	33.3	12	44.4	6	2.3	9	42.9	96	36.2
ER 6	0	0.0	2	4.2	0	0.0	0	0.0	0	0.0	5	1.9
ATA												
IR 15	1	1.5	0	0.0	0	0.0	0	0.0	0	0.0	1	0.4
IR 12	0	0.0	0	0.0	1	3.7	1	4.0	1	4.8	5	1.9
IR 9	5	7.7	10	20.8	4	14.8	0	0.0	2	9.5	23	8.7
IR 6	20	30.8	7	14.6	4	14.8	6	24.0	3	14.3	61	23.0
IR 3	23	35.4	14	29.2	9	33.3	9	36.0	11	52.4	88	33.2
NEU	**10**	**15.4**	**12**	**25.0**	**8**	**29.6**	**6**	**24.0**	**4**	**19.0**	**70**	**26.4**
ER 3	5	7.7	4	8.3	0	0.0	2	8.0	0	0.0	13	4.9
ER 6	1	1.5	1	2.1	1	3.7	1	4.0	0	0.0	4	1.5

The bold indicated Neutra values.

NEU, neutral; VAR, varus; VAL, valgus; IR, internal rotation; ER, external rotation; FMA, femoral mechanical angle; TMA, tibial mechanical angle.

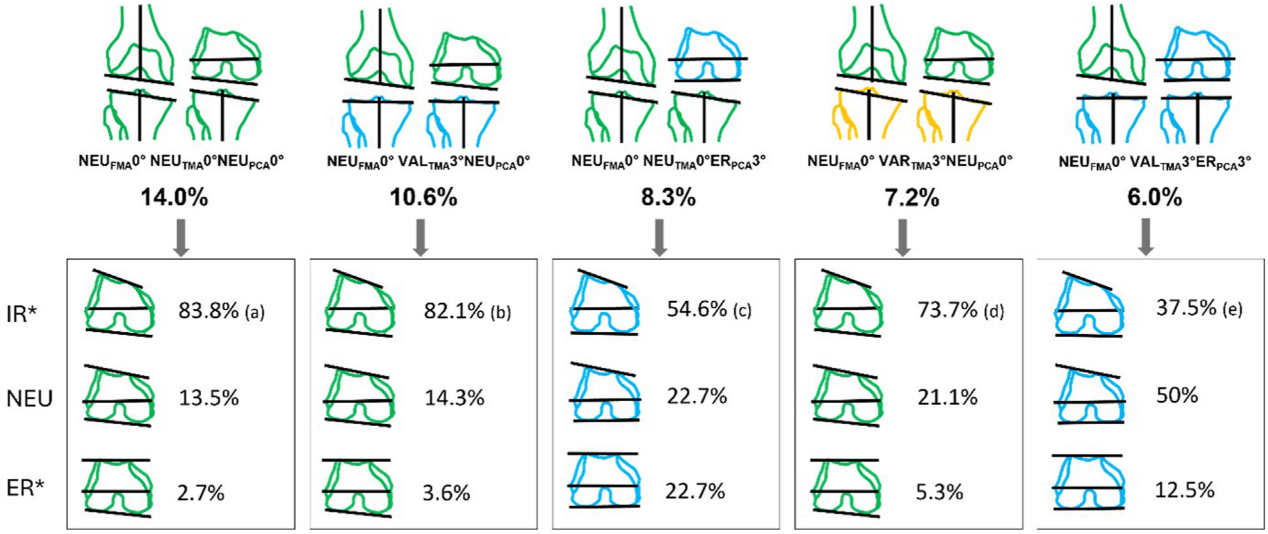

Figure 3. Frequency of the anterior femoral joint line phenotypes (based on the anterior trochlear angle [ATA]) in the most common surgical phenotypes (FMA + TMA + PCA) in nonosteoarthritic knees. TMA, tibial mechanical angle; FMA, femoral mechanical angle; PCA, posterior condylar angle.

magnitude and clinical relevance of this difference are debated [52]. Our study adds to this knowledge by describing the internal/external rotation of the trochlea and by assessing the effect in the context of different alignment concepts with the aid of phenotypes. The anterior femoral joint line thereby seems more internally rotated than the posterior femoral joint line in the majority of patients and is thus rotated externally regardless of the alignment concept. However, the postoperative anterior femoral joint line might be internally rotated in patients where the ATA is more externally rotated than the PCA or when the femur component is internally rotated to fit a specific alignment concept. Figures 4 through 6 illustrate this effect and show how different alignment strategies lead to different changes in alignment. The above-mentioned study by Rivière et al. also assessed the change in trochlear geometry and reported an overstuffing of the lateral facet and the groove only in deep flexion [18]. This seems to be in

Table 7
The Distribution (Shown in Percent) of the Nonosteoarthritic (OA) and OA Population Among the Different Phenotypes.

Non-OA Population							OA Population				
	Flexion Phenotype	PCA					PCA				
		IR 6	IR 3	NEU	ER 3	ER 6	IR 6	IR 3	NEU	ER 3	ER 6
TMA	VAL 9			0.4							
	VAL 6			0.4	1.9	0.4[a]		0.2	1.7	1.1	[a]
	VAL 3		1.5	15.8	11.3[a]	0.8		1.8	8.7	6.3[a]	0.7
	NEU	0.4	3.8	22.6[a]	16.6	0.4	0.1	3.7	21.2[a]	14.5	1.2
	VAR 3	0.4	1.1[a]	12.8	4.9	0.4		2.7[a]	15.5	9.8	0.8
	VAR 6	[a]	0.4	2.3	1.5		[a]	0.8	4.1	2.9	0.1
	VAL 9							0.1	0.8	0.4	0.1
Femur phenotype											
FMA	VAL 9								0.1	0.1	
	VAL 6	[a]		1.1	1.1		0.1[a]	0.7	1.9	0.7	0.1
	VAL 3		2.6[a]	11.7	9.4			2.7[a]	10.8	6.5	0.4
	NEU	0.4	3.0	33.6[a]	18.9	1.1		3.7	23.4[a]	15.1	1.2
	VAR 3	0.4	1.1	7.5	6.8[a]	0.8		1.8	14.2	10.6[a]	0.9
	VAR 6			0.4		[a]		0.2	1.7	1.9	0.3[a]
	VAR 9							0.2	0.2	0.3	
Rotational phenotype											
ATA	ER 6				1.5	[a]					
	ER 3			1.5	2.6[a]	0.8					
	NEU	0.4	1.5	9.1[a]	14.7	0.8					
	IR 3		2.3[a]	19.2	11.3	0.4					
	IR 6	0.4[a]	1.9	16.2	4.5						
	IR 9		0.8	6.8	1.1						
	IR 12		0.4	1.1	0.4						
	IR 15			0.4							

NEU, neutral; VAR, varus; VAL, valgus; IR, internal rotation; ER, external rotation; FMA, femoral mechanical angle; TMA, tibial mechanical angle; PCA, posterior condylar angle; ATA, anterior trochlear angle.

[a] combination of phenotype with parallel joint lines (e.g., $FMA_{neu}0^{\circ}PCA_{neu}0^{\circ}$).

Table 8
The Distribution (Shown in Percent) of the Nonosteoarthritic (OA) and OA Population Among the Surgical Phenotypes.

Non-OA Population						OA Population				
TMA VAL 6[b]	PCA									
	IR 6	IR 3	NEU	ER 3	ER 6	IR 6	IR 3	NEU	ER 3	ER 6
FMA										
VAL 6	[a]				[b]					
VAL 3		[a]		0.8						
NEU			0.4[a]	0.8	0.4					
VAR 3				0.4[a]						
VAR 6					[a]					
VAR 9										
TMA VAL3[b]	IR 6	IR 3	NEU	ER 3	ER 6					
FMA										
VAL 6	[a]					[a]	0.1	1.2	0.5	
VAL 3		0.8[a]	3.8	3.4[b]			0.9[a]	2.5	1.6[b]	0.1
NEU		0.8	10.6[a]	6.0	0.8		1.2	4.6[a]	2.5	0.1
VAR 3			1.5	1.9[a]			0.4	1.9	1.3[a]	
VAR 6					[a]		0.2	0.6	0.5	[a]
VAR 9								0.1		
TMA NEU[b]										
FMA										
VAL 6	[a]		0.8	0.4		[a]		0.2	0.5	
VAL 3		0.8[a]	4.9	4.5			0.6[a]	3.9	2.6	0.3
NEU	0.4	1.9	14.0[b]	8.3			1.5	9.1[b]	6.4	0.4
VAR 3		1.1	2.6	3.4[a]	0.4		1.2	7.5	4.4[a]	0.5
VAR 6			0.4		[a]		0.3	2.1	1.0	[a]
VAR 9								0.4	0.2	
TMA VAR3[b]										
FMA										
VAL 6	[a]		0.4	0.8		[a]				
VAL 3		1.1[a]	2.3	0.8			0.2[a]	1.5	1.7	0.2
NEU			7.2[a]	2.3			0.4	6.3[a]	4.8	0.4
VAR 3	0.4	[b]	3.0	1.1[a]	0.4		0.9[b]	5.2	3.0[a]	0.2
VAR 6					[a]		0.2	1.0	1.0	[a]
VAR 9								0.2	0.1	
TMA VAR6[b]										
FMA										
VAL 6	[a]					[a]				
VAL 3		[a]	0.8				[a]		0.3	
NEU		0.4	1.1[a]	1.5				0.6[a]	0.5	0.1
VAR 3			0.4	[a]			0.1	0.7	0.8[a]	
VAR 6	[b]				[a]	[b]		0.3	0.4	[a]
VAR 9										

NEU, neutral; VAR, varus; VAL, valgus; IR, internal rotation; ER, external rotation; FMA, femoral mechanical angle; TMA, tibial mechanical angle; PCA, posterior condylar angle; ATA, anterior trochlear angle.

[a] combination of femur phenotype with parallel joint lines (e.g., $FMA_{neu}0^\circ PCA_{neu}0^\circ$).

[b] phenotypes where TMA equals PCA (e.g., the flexion gaps is parallel).

accordance with our data because the lateral facet and groove were deeper in the prosthetic setting for most of the course of the trochlea, which is probably due to the external rotation of the component, even if aligned according to the distal femoral joint line. Huber et al. simulated an unrestricted kinematic alignment in 100 patients and assessed the frequency with which the component alignment would have been outside predefined safe zones [53]. In 51% of all cases, the alignment had to be adapted most frequently because the orientation of the trochlear axis would have been outside the safe zones. No details were provided regarding the magnitude or direction of the changes required to align the prostheses. Finally, Corbett et al. most recently assessed the correlations between coronal and rotational alignment parameters using the Coronal Plane Alignment of the Knee classification. Similar to the

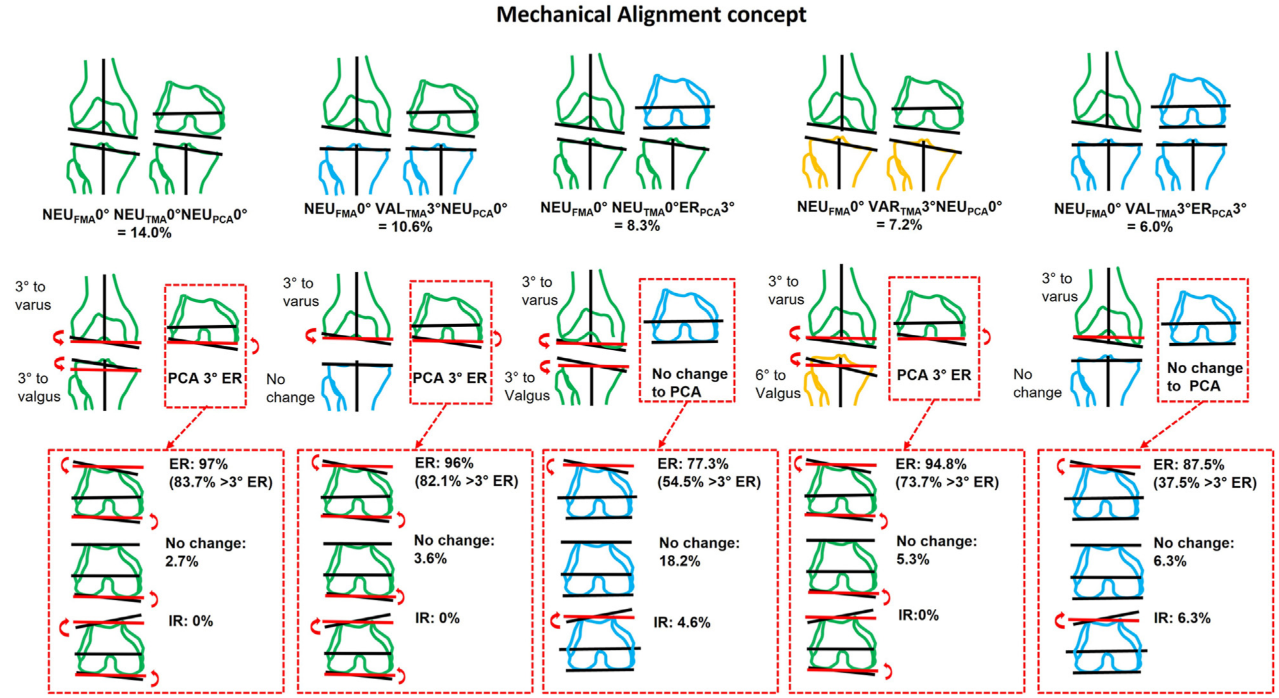

Figure 4. The 5 most common phenotypes of the nonosteoarthritic population and the change in joint line orientation when a mechanical alignment concept is simulated. Black lines represent joint lines and mechanical axis, and red lines represent changes in joint line orientation. The color of the bone represents the phenotype (e.g., green = neutral phenotype, blue = valgus/external rotation phenotype, yellow = varus). The percentage of patients who had a change in anterior trochlear angle (ATA) orientation corresponds to the phenotype (e.g., in the most common phenotype, a change in ATA would occur in 97%).

results of this study, none or only weak correlations were found [30]. Interestingly, the authors concluded that an extension of the Coronal Plane Alignment of the Knee concept would not be beneficial. In contrast, the authors of this study would argue that extending the FKP concept to include rotational alignment parameters is beneficial because there is no correlation between

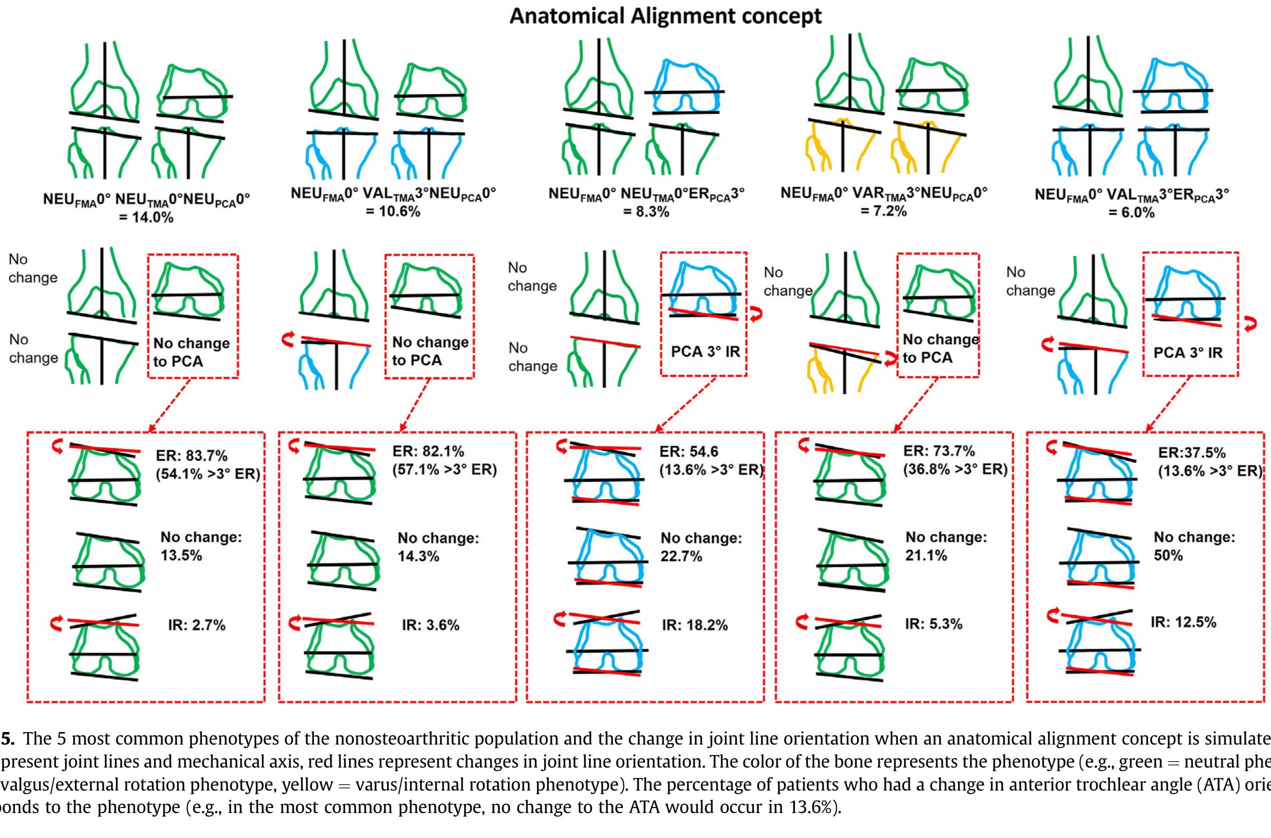

Figure 5. The 5 most common phenotypes of the nonosteoarthritic population and the change in joint line orientation when an anatomical alignment concept is simulated. Black lines represent joint lines and mechanical axis, red lines represent changes in joint line orientation. The color of the bone represents the phenotype (e.g., green = neutral phenotype, blue = valgus/external rotation phenotype, yellow = varus/internal rotation phenotype). The percentage of patients who had a change in anterior trochlear angle (ATA) orientation corresponds to the phenotype (e.g., in the most common phenotype, no change to the ATA would occur in 13.6%).

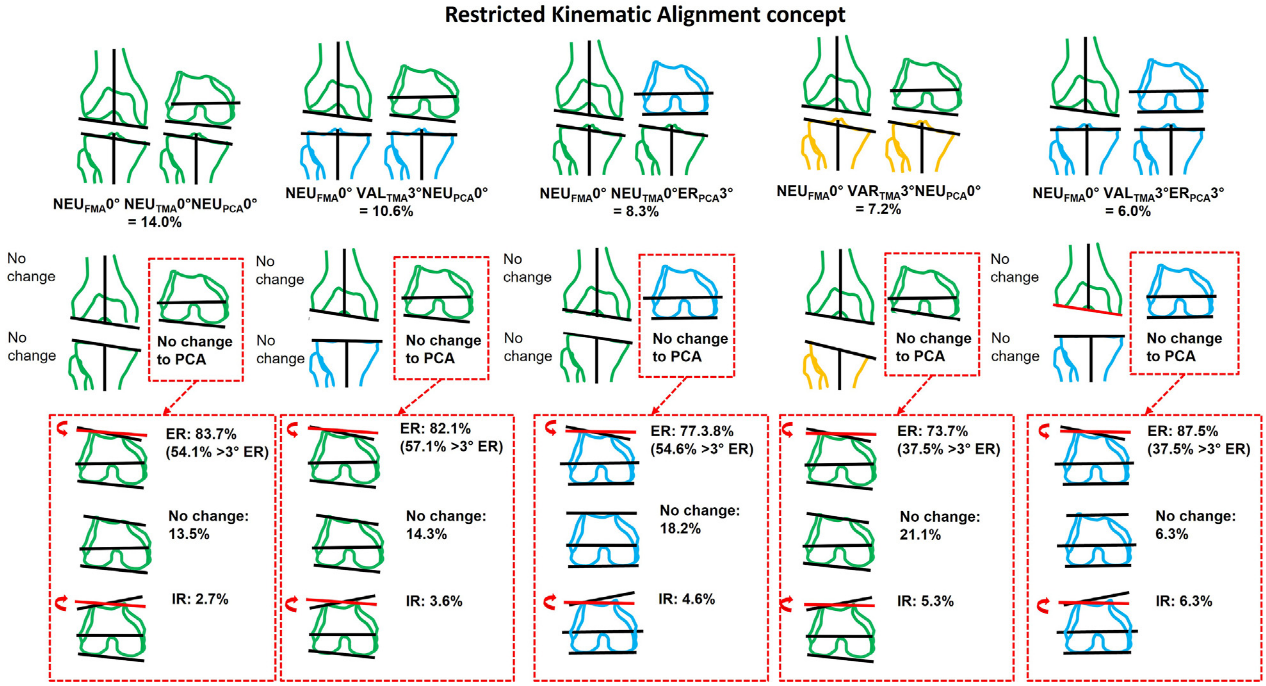

Figure 6. The 5 most common phenotypes of the nonosteoarthritic population and the change in joint line orientation when a restricted kinematic alignment concept is simulated. Black lines represent joint lines and mechanical axis, and red lines represent changes in joint line orientation. The color of the bone represents the phenotype (e.g., green = neutral phenotype, blue = valgus/external rotation phenotype, yellow = varus/internal rotation phenotype). The percentage of patients who had a change in anterior trochlear angle (ATA) orientation corresponds to the phenotype (eg in the most common phenotype, no change to the ATA would occur in 13.6%).

coronal and axial alignment. Patients who had the same coronal variation (= coronal phenotype) seem to have different rotational alignment variations (= rotational phenotypes); thus, extending the concept seems clinically useful. If coronal and axial parameters were strongly correlated, then an extension would be of no value because all patients who had the same coronal phenotype would have the same rotational phenotype.

Our study had several potential limitations, and our results should therefore be interpreted with caution. Measurements were based on bony landmarks only, disregarding variations in cartilage thickness, and differences in laxity between the medial and lateral sides (in extension and flexion) were not considered. Yet, our findings are still of relevance because preoperative planning and some intraoperative techniques are based on the same bony landmarks and are subject to the same limitations. The study has a risk for a selection bias as only patients who had progressed OA patients are represented within the Knee-PLAN 3D database. However, this is one of the largest samples investigated, and ranges of the alignment parameters were comparable to previously reported ranges. Similarly, all non-OA patients presented themselves to our clinic with problems in one or both knees and might exhibit different alignment characteristics than the general population. Nevertheless, stringent inclusion and exclusion criteria, coupled with initial analyses, excluded patients who had severe alignment deformities. The OA grades were not available for analysis, and it has been shown that the grade of OA influences overall alignment. Our knowledge regarding patient characteristics was limited to age, sex, and information visible on CT images.

Conclusions

Based on our findings and existing literature, it is crucial to emphasize that the preoperative assessment of a patient's anatomy should not only include the distal femoral and proximal tibial joint lines, but also the anterior and posterior femoral joint lines. The extended FKP concept introduced here could aid in this assessment and help identify patients at risk of complications due to malalignment or those benefiting from a particular alignment concept or customized implant.

CRediT authorship contribution statement

Silvan Hess: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Sabrina Chelli:** Writing – review & editing, Writing – original draft, Validation, Methodology, Data curation, Conceptualization. **Vincent Leclercq:** Writing – original draft, Visualization, Validation, Formal analysis, Data curation, Conceptualization. **Sébastien Lustig:** Writing – review & editing, Writing – original draft, Validation, Methodology. **Heiko Graichen:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision. **Michael T. Hirschmann:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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