MENTORS IN ORTHOPEDICS

THE "FUNCTIONAL KNEE PHENOTYPE CONCEPT" AND ITS IMPACT ON THE CONTROVERSY OF PROPER FRONTAL ALIGNMENT IN TKA

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SUMMARY

Background: While total knee arthroplasty (TKA) is the standard treatment for end-stage osteoarthritis, the optimal alignment strategy remains a subject of significant debate. Traditional mechanical alignment aims for a neutral axis, yet approximately 20% of patients report dissatisfaction, potentially due to alterations in native joint kinematics and the requirement for extensive soft tissue releases.

Objective: This article reviews contemporary TKA alignment concepts, including mechanical, anatomical, constitutional, and kinematic approaches, while introducing the functional knee phenotype concept (KPC) as a framework for individualized surgical planning.

Key Points: Mechanical alignment remains the clinical benchmark despite challenges to its necessity for implant longevity. Anatomical alignment attempts to recreate native joint line obliquity, while constitutional alignment allows for residual varus to avoid extensive releases. Kinematic alignment focuses on restoring pre-arthritic bony morphology and soft tissue tension. The KPC, derived from non-osteoarthritic population data, identifies significant variability in femoral mechanical angles (FMA) and tibial mechanical angles (TMA). Analysis reveals that a strictly neutral mechanical joint line (FMA 90°, TMA 90°) occurs in less than 4% of the population. The KPC categorizes patients into specific phenotypes based on limb, femoral, and tibial alignment, suggesting that a single alignment target may not accommodate the diverse anatomical variations observed clinically.

Conclusion: The functional knee phenotype concept provides a standardized, evidence-based classification for understanding native alignment variability. By clustering patients into specific phenotypic groups, surgeons may transition toward more personalized alignment strategies to potentially improve functional outcomes and restore natural knee kinematics.

KEYWORDS

Arthroplasty, Replacement, Knee; Bone Malalignment; Knee Joint; Osteoarthritis, Knee; Phenotype

INTRODUCTION

Despite the general acceptance of TKA as the treatment of choice in end stage osteoarthritis, the best method of performing a TKA is still under debate. The optimal implant alignment is only one topic among many others, but it has increasingly gained attention for many knee surgeons (1). Currently there are at least five different alignment concepts promoted, which have led to some confusion among knee surgeons as differences between these concepts are often not understood well enough (2) (Figure 1). Currently there is no evidence that one of these concepts will be more beneficial for the patient with regards to the functional outcome or long-term survival.

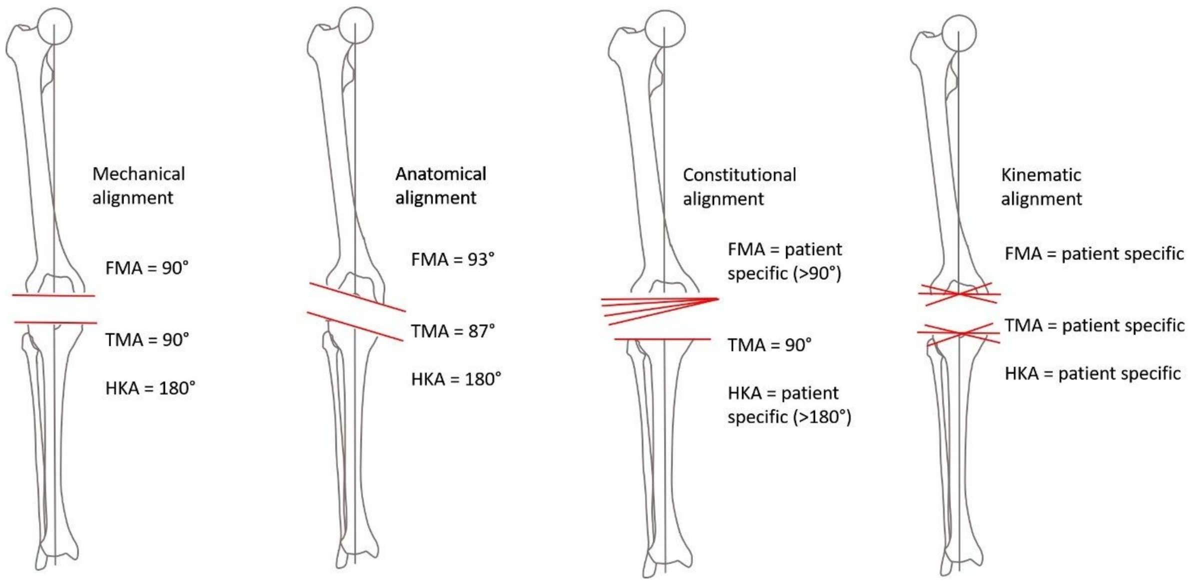


Figure 1: Different Alignment Options for TKA

Recent papers proved that there is a very wide anatomical variation in the deformity of the knee in the young non-osteoarthritic knees planned for TKA (3–8). The concept of "deformity analysis" to investigate this broad variation has been described by D. Paley more than 20 years ago for osteotomies (9). However, this simple analysis on full leg films has unfortunately not been widely used by knee surgeons for their TKA planning (9). On the other hand, this deformity analysis builds the foundation for computer navigation, patient specific cutting blocks and recently robotic surgery (10).

In this paper the different alignment concepts for TKA will be described and the possible Pros and Cons presented. The new functional knee phenotype concept will be explained and its impact on the frontal alignment controversy will be discussed.

MECHANICAL ALIGNMENT

For decades the mechanical alignment concept introduced by Michael Freeman has been the "gold standard" for TKA (11). Based on old biomechanical and clinical studies, a mechanical neutrally aligned lower limb with joint lines perpendicular to the mechanical axes has been promoted as the goal for the last 40 years (12). Excellent long-term implant survivorship and a relatively high patient satisfaction rate have been achieved with this concept, which is why it still remains the alignment concept of choice for most surgeons (1). However, the superiority of the mechanical alignment concept has been repeatedly questioned over the last decades. Parratte et al. challenged the long-held dogma of "malaligned" TKA being associated with decreased durability (13). Furthermore, since its introduction surgeons recognized that this systematic approach leads to a significant alteration of the patient's native anatomy, which results in new artificial biomechanics and the need for some soft tissue releases in most of the cases. Opponents of this concept claim that this has a negative impact on the functionality and kinematics and might be the major cause for the 20 % unsatisfied TKA patients (2,14).

ANATOMICAL ALIGNMENT

In 1980s, Hungerford and Krackow already proposed the anatomical alignment concept, which aims to improve functionality by recreating a more native joint line orientation (15). An oblique joint line orientation (frontal bone cuts femur 3° valgus and tibia 3° varus) which better mimics the average native joint line orientation was promoted as goal. This was the first alternative alignment concept and implicated a better load distribution on the tibial component, better patellar kinematics and reduced risk for lateral ligament stress (16,17). Despite these theoretical advantages, clinical results did not show any benefits and concerns regarding the risk of excessive varus tibia alignment and increased wear prevented the wide spread of this concept. Subsequently, the mechanical alignment concept remained the gold standard until today.

CONSTITUTIONAL ALIGNMENT

Bellemans et. al. highlighted the fact that most people do not have a straight lower limb. In his classical paper, they showed that in a young and healthy population nearly 36% of the male and 17% of the female had a constitutional varus knee malalignment (represented by a hip-knee-ankle angle (HKA) < 177°) (18). Consequently, they questioned the tenet to correct all patients to neutral alignment, which will need unnecessary soft tissue releases and change their natural biomechanics. With this new approach they introduced the concept of "constitutional alignment", which will leave varus and valgus knees in some residual under correction. They proposed to perform under correction at the femur and place the tibia in 90° to the mechanical axis. This will allow a more patient specific alignment and to perform no releases in non-severe and less releases in more deformed knees. The same research group retrospectively assessed clinical and radiological outcome of 143 patients with medial knee OA and a preoperative varus alignment (19). At a mean follow up of 7.2 years, patients with a mild postoperative varus showed significantly better KSS and WOMAC score than patients with a severe varus or neutral postoperative alignment. The mal-aligned group did not have an inferior survivorship compared to the well aligned TKA group. However, none of patients needed revision during this follow up midterm. Opponents of this concept claim that there are conflicting outcomes published and there is no evidence in RCT studies, that constitutional alignment will have a benefit for TKA patients compared to mechanical alignment. Furthermore, the limit of under correction is not clear and the alignment, with correction at the femur only is not a natural one.

KINEMATICAL ALIGNMENT

The biomechanical basis for TKA goes back to Hollister et al, who published the kinematic axis for the knee already in 1993 (20). Kinematic alignment (KA) for TKA was already introduced by Howell in combination with patient specific cutting blocks in 2008 (21). The concept is pure cartilage restoration without corrections of bony deformities in any of the three planes. The target is to restore the pre-arthritic alignment and kinematics of the knee to allow more natural biomechanics, no releases and better function (14). The KA concept is promoted mainly by Howell and his group. They claim no limitations for deformities, no intraoperative problems, not more complications, better functional outcome and long-term survival up to 10 years comparable to mechanical alignment (22). Many KA surgeons do not follow the pure KA concept and perform restricted KA by selecting patients with non-severe deformities and allow limited residual malalignment after TKA only (23).

Conflicting results have been published in several studies reporting better outcomes for KA in comparison to mechanical alignment (14,22,24), while others did not find any differences (25–27). So far long- term data for KA are only available from one research group (22). Opponents of this concept claim that the clinical benefit is not proven, patient selection is still not clear, the surgical technique to adapt the tibia bone cuts to the soft tissue frame is difficult and the risk for varus malalignment especially at the tibia is underestimated by KA surgeons (28–30).

FUNCTIONAL KNEE PHENOTYPE CONCEPT

Breaking long-held dogmas can cause a certain amount of uncertainty, but it can also be seen as an opportunity to reassess our knowledge about alignment and build an evidence-based foundation for a more patient-specific approach to TKA.

The recently introduced functional “knee phenotype concept” (KPC) might play an important role in this movement. The concept is based on the alignment analysis of a young non-OA population of 308 knees and enables a new and comprehensive way to evaluate the frontal knee alignment and implant orientation (3–5). The concept was further validated using data on osteoarthritic knees. Until now, the discussion regarding the optimal frontal alignment has been focused on the influence of the overall alignment or a certain alignment concept on the clinical outcome only. However, the analysis of the coronal alignment of a young non-OA population showed that is approach might be short-sighted (3–5). Not only the overall lower limb alignment (represented by the HKA) is very variable but also the orientation of the femoral and tibial joint line represented by the femoral mechanical angle (FMA) and tibial mechanical angle (TMA) (Figure 2) (5).

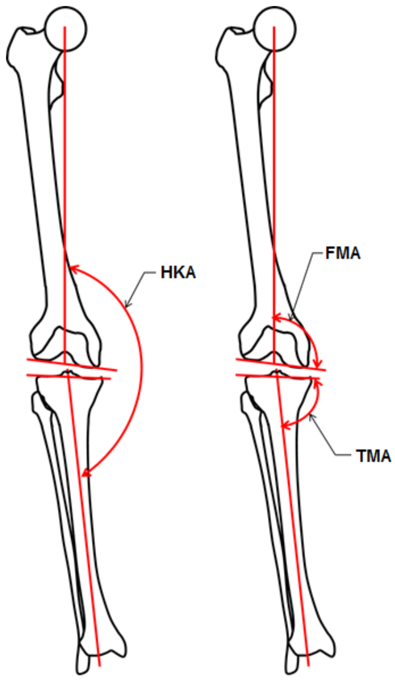


Figure 2: Key alignment angles in frontal planeHip-knee-ankle (HKA), femur mechanical angle (FMA) and tibia mechanical angle (TPA)

Others have previously highlighted the variability of the anatomy in OA and native knees, but data on native knees has been limited and investigations have mainly been restricted to mean values or ranges of each angle separately (18,31,32). It is important to understand that when assessing and comparing only mean values or ranges of one angle independently, critical information is lost.

A completely new picture emerges when the KPC is used to analyse the individual alignment based on phenotypes. A phenotype thereby either represents a coronal alignment variation of the femur (femoral phenotype), the tibia (tibial phenotype) or the overall lower limb (limb phenotype). Each alignment variation is based on specific angles (FMA for the femur, TMA for the tibia and HKA for the overall limb) and each phenotype represents a range of ±1.5° from a phenotype specific mean value. The name of phenotypes thereby contains of three parts. Part 1 defines the direction of deviation (NEU, VAR, VAL) from the overall mean value of the angle, part two defines the phenotype specific angle (second subscripted part: HKA, FMA, or TMA) and part 3 the average deviation from the mean values (0°, 3° and 6°) (Fig 3).

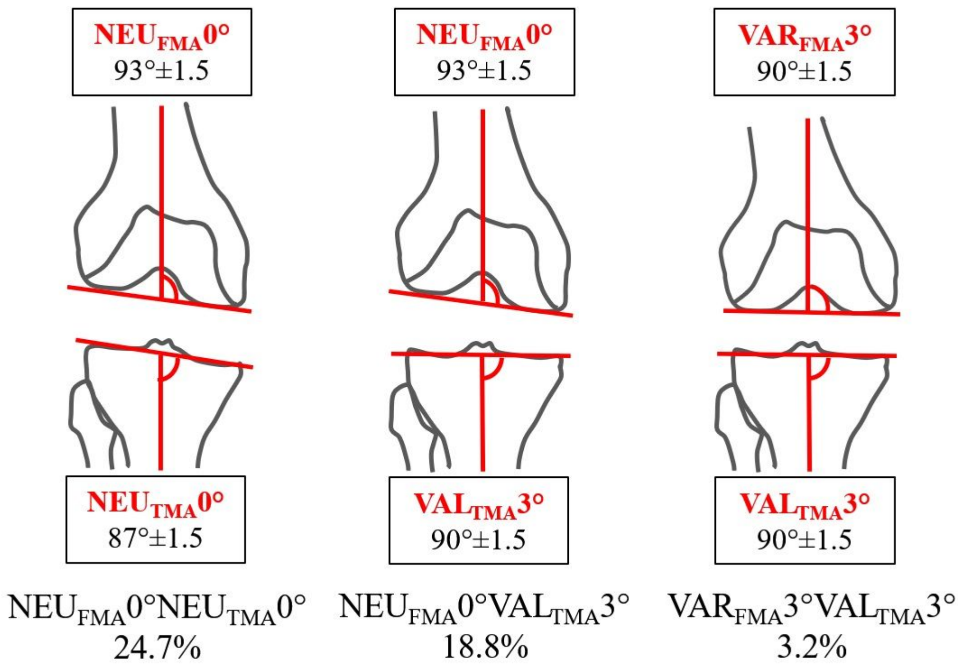


Figure 3: The three most common knee phenotypes and the prevalence in the young non-OA population.

For example, the most common femoral alignment variation (i.e. femoral phenotype) was NEUFMA0°, which means that most patients had a femoral mechanical angle within the range of 93° ± 1.5. The innovative part of the functional knee phenotype is the combination of the different phenotypes into knee phenotypes (combination of femoral and tibial phenotypes) and functional knee phenotypes (combination of all three phenotypes). Combining femoral and tibial phenotypes revealed that the most common knee phenotype with 24,7% matched the joint line orientation of the anatomical alignment concept (FMA = 93°± 1.5, TMA = 87°± 1.5 = NEUFMA0°NEUTMA0°). A substantial part of the population (18.8%) had a normal femur (FMA = 93°±1.5; NEUFMA0°) and a slight valgus tibia (TMA 90°±1.5= VALTMA3°). While mechanical joint line orientation (FMA = 90°± 1.5, TMA = 90°± 1.5 = VARFMA3°VALTMA3°) on the other hand was found in less than 4% of the population.

The most interesting part of the functional KPC is the combination of all three phenotypes (limb, femur and tibia). This showed that the orientation of the femoral and tibial joint lines is much more variable within a limb phenotype (e.g. a population of patient with a similar HKA) than expected. In the population of patients with a neutral limb phenotype (HKA within the range of 180°± 1.5; limb phenotype NEUHKA0°) nine different combinations of femoral and tibial joint line orientation were found (i.e. knee phenotypes). Similarly, in the population with a slight varus overall lower limb alignment (HKA within the range of 177°±1.5; limb phenotype VARHKA3°), ten different knee phenotypes were found (4). Table 1 summarizes the distribution of the functional knee phenotypes in young and non-osteoarthritic knees.

Category	Deviation	Name	Mean value	Range
Limb phenotypes (Hip-knee-ankle angle; HKA)	VAR_{HKA}	VARHKA9°	171°	169.5°<HKA<172.5°
		VARHKA6°	174°	172.5°<HKA<175.5°
		VARHKA3°	177°	175.5°<HKA<178.5°
	NEU_{HKA}	NEUHKA0°	180°	178.5°<HKA<181.5°
	VAL_{HKA}	VALHKA3°	183°	181.5°<HKA<184.5°
		VALHKA6°	186°	184.5°<HKA<187.5°
		VALHKA9°	189°	187.5°<HKA<190.5°
Femoral phenotypes (Femoral mechanical angle; FMA)	VAR_{FMA}	VARFMA6°	87°	85.5°<FMA<88.5°
		VARFMA3°	90°	88.5°<FMA<91.5°
	NEU_{FMA}	NEUFMA0°	93°	91.5°<FMA<94.5°
	VAL_{FMA}	VALFMA3°	96°	94.5°<FMA<97.5°
		VALFMA6°	99°	97.5°<FMA<100.5°
Tibial phenotypes (Tibial mechanical angle; TMA)	VAR_{TMA}	VARTMA6°	81°	79.5°<TMA<82.5°
		VARTMA3°	84°	82.5°<TMA<85.5°
	NEU_{TMA}	NEUTMA0°	87°	85.5°<TMA<88.5°
	VAL_{TMA}	VALTMA3°	90°	88.5°<TMA<91.5°
		VALTMA6°	93°	91.5°<TMA<94.5°

By enabling a different view on the alignment, the functional knee system could potentially have a significant impact on the discussion surrounding the optimal TKA alignment. Taking the example from above and linking it to TKA is a simple way to illustrate the advantage of the functional knee phenotype concept. If patients with a neutrally aligned limb have nine differently orientated femoral and tibial joint lines, why should a mechanical alignment be the optimal alignment for all of these patients?

Moreover, if the joint line orientation differs among neutral aligned patients, the impact of different alignment concept might vary significantly. Figure 4 shows the two most common phenotypes and the impact of the two alignment concepts in terms of change in joint line orientation. In the first case with NEUHKA0°NEUFMA0°NEUTMA0° (HKA: 180° ±1.5; FMA: 93° ±1.5; TMA: 87° ±1.5) when mechanical alignment concept is followed the orientation of tibial and femoral joint lines are changed and when performing the anatomical alignment concept, no change is needed for both joint lines. In the second case with NEUHKA0°NEUFMA0°VALTMA3° (HKA: 180° ±1.5; FMA: 93° ±1.5, TMA: 90° ±1.5) both concepts result in a change of 3° but either only in the femur (mechanical alignment concept) or only in the tibia (anatomical alignment concept).

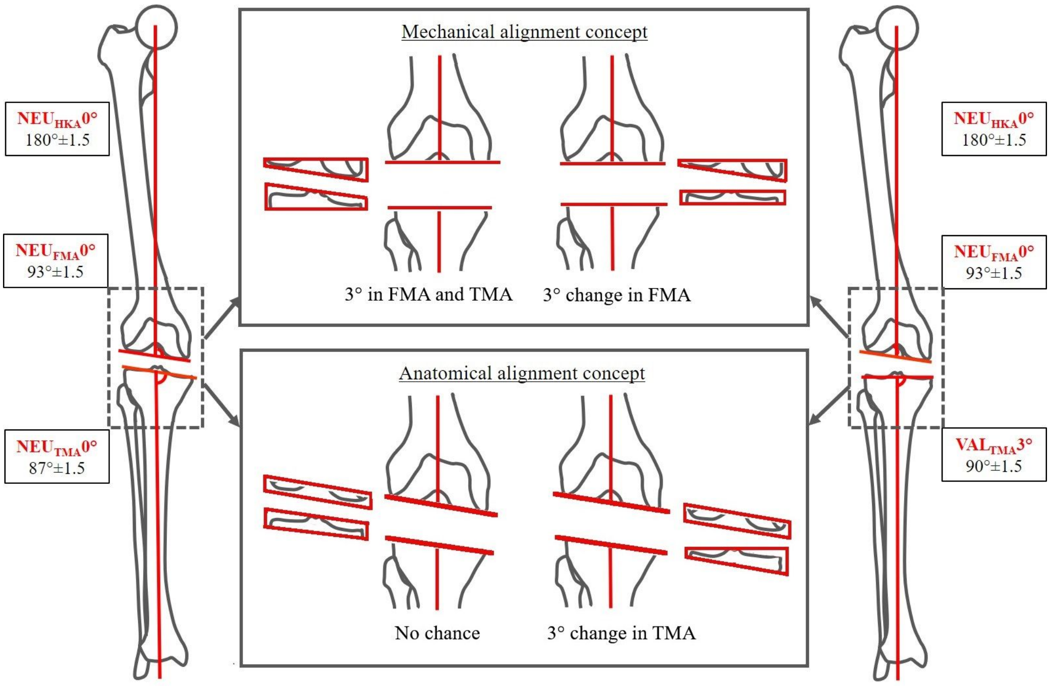
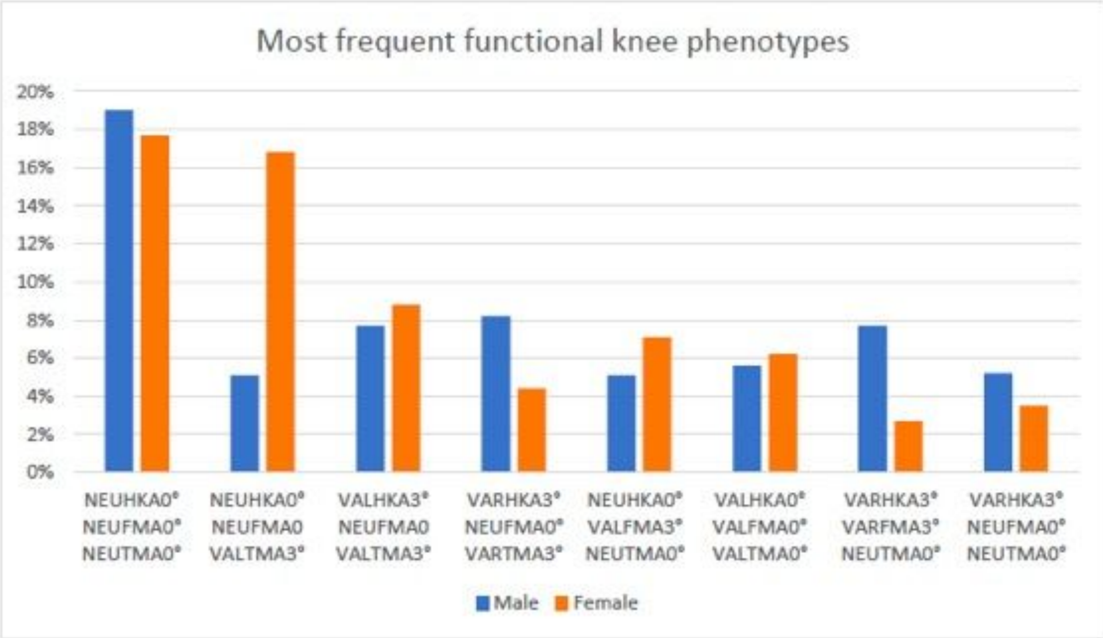


Figure 4: The impact of the mechanical and anatomical alignment on the two most common functional knee phenotypes.

It can also be seen that depending on the knee phenotype of a patient and the utilized alignment concept, collateral ligament offsets and soft tissue envelope strains are altered in a different way. This might have the biggest impact on knee function after TKA and may partly explain why studies assessing the connection between change in alignment (pre-to post) and clinical outcome reported conflicting results. In fact, a potential additional advantage of the functional knee phenotype concept might be that patients with a similar alignment can be clustered together. This limits the complexity of the system and acknowledges the fact that small differences or changes to the alignment might not affect the clinical outcome.

What could be the specific consequences of the KPC on our everyday clinical work? Until now, the practical impact of the functional knee system is limited because clinical studies using the system are missing. Nevertheless, the possible applications of the system seem to be straight forward. For example, based on previous studies (19), we know that patients with a preoperative varus alignment might benefit from a postoperative alignment, which is still in slight varus. The second most common phenotypes in the study by Hirschmann and colleagues was VARHKA3°VARFMA3°NEUTMA0° (HKA 177°±1.5; FMA: 90°±1.5; TMA: 87°±1.5).



It seems to be reasonable that for this type of OA patients (mainly females), the optimal prosthesis orientation might be this phenotype. Continuing this thought, based on further research, it might be possible to propose the use of a certain phenotype alignment concept or alignment variation (i.e. functional knee phenotype) for a specific patient or rather groups of patients with a specific functional knee phenotype. The functional knee phenotype concept therefore could be a useful tool for a more patient-specific approach in TKA surgery.

However, it seems important to note that this approach does not favour or exclude the use of one specific alignment concept. It should instead foster an open and evidence-based discussion about the benefits and risk associated with the use of an alignment concept for a specific group of patients. It is obvious that the functional knee phenotype system can be seen as work in progress. An assessment not only of the frontal, but also of the sagittal, rotational and femoral-patellar alignment seems to be essential. The most important point will be to adapt the functional KPC to osteoarthritic knees scheduled for TKA, since the deformities are significantly different to the deformities used in the previous study (Hess, KSSTA 2019, Springer, KSSTA 2019). Lastly, clinical studies will have to show a clear benefit for the patient.

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