The best and most beautiful things in the world cannot be

seen or touched, they must be felt with the heart

Hellen Keller

In the end, it’s not going to matter how many breaths you took, but how many moments took your breath away

Shing Xiong

Faculty of Medicine and Health Sciences, Ghent University

Alignment in Total Knee Arthroplasty: Analysis of Surgical Accuracy

Emmanuel Thienpont, MD, MBA

Doctoral thesis submitted to fulfil the requirements for the degree of
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Promotor Jan Victor, MD, PhD

Second Promotor Johan Bellemans, MD, PhD

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	Matthias Verstraete, Ir, PhD Universiteit Gent, Ghent, Belgium

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Abbreviations

2D	Two-dimensional
3D	Three-dimensional
ACL	Anterior Cruciate Ligament
ADL	Activities of Daily Living
aLDFA	anatomical Lateral Distal Femoral Angle
AMA	angle between the Anatomical and Mechanical Axis
AP	AnteroPosterior
ARS	Audience Response System
BMI	Body Mass Index
CAS	Computer-Assisted Surgery
CH	Condylar Hip
CP	Condylar Plateau
CT	Computed Tomography
DF	Deformity at the Femoral level
DT	Deformity at the Tibial level
DTF	Deformity at the Tibial and Femoral level combined
FJS-12	Forgotten Joint Score-12
FOV	Field-Of-View
HKA	Hip-Knee-Ankle
HTO	High Tibial Osteotomy
IA	Intra-Articular
JLCA	Joint Line Congruency Angle
KOOS	Knee injury and Osteoarthritis Outcome Score
KSS	Knee Society Score
LBA	Load Bearing Axis
LDFA	Lateral Distal Femoral Angle
mLDFA	mechanical Lateral Distal Femoral Angle
MIS	Minimally Invasive Surgery
MOA	Medial OsteoArthritis
MPTA	Medial Proximal Tibial Angle
MRI	Magnetic Resonance Imaging
OA	OsteoArthritis
PA	Plateau Angle
PFA	PatelloFemoral Arthroplasty
PFJ	PatelloFemoral Joint
PFOA	PatelloFemoral OsteoArthritis
PMOA	PosteroMedial OsteoArthritis
PPSP	Persistent PostSurgical Pain
PRISMA	Preferred Reporting Items for Systematic reviews and Meta-Analyses
PROM	Patient-Reported Outcome Measure
PS	Posterior Stabilized
PSI	Patient-Specific Instrumentation
QOL	Quality Of Life
RCT	Randomized Controlled Trial

RR	Risk Ratio
SD	Standard Deviation
TKA	Total Knee Arthroplasty
UKA	Unicompartmental Knee Arthroplasty

Alignment in Total Knee Arthroplasty: Analysis of Surgical Accuracy

Chapter I: Introduction to limb alignment, component positioning and accuracy

Knee osteoarthritis (OA) is an increasing burden for our modern society[1,2]. This epidemic is related to the current demographic pattern that is developing with a population that is getting older but still remaining active. OA is the result of a multifactor evolution that leads finally to end-stage arthritis. Several factors are contributing to this disease, including age, sex, body mass index (BMI), and lower limb alignment. Whenever conservative treatment of OA comes to an end and bone-on-bone OA is reached, knee arthroplasty might be indicated[3].

Knee arthroplasty can be partial in case of limited and localized disease, and performed either with medial or lateral unicompartmental knee arthroplasty (UKA) or with patellofemoral arthroplasty (PFA). However, knee arthritis can also involve several compartments of the joint and in that case total knee arthroplasty (TKA) is used. TKA is an invasive surgery that requires surgical expertise and knowledge about anatomy and biomechanics of the knee joint. The knee has three planes; the axial, coronal, and sagittal plane and accuracy in each plane is needed to obtain a successful joint replacement. The axial plane has been extensively studied for its ideal alignment, both for gap stability and patellar tracking[4-10]. Coronal alignment has historically been linked to polyethylene wear and early failure[11,12].
Approximately 80% of patients who undergo TKA are satisfied with their surgery, but there is a segment of the surgical population that complains about persistent postsurgical pain (PPSP)[13,14] or other complications, like stiffness[15], instability[15] or malalignment[16]. Malalignment has routinely been linked to an increased risk of wear and loosening[17]. Recent literature has refuted these hypotheses, with several papers showing that neutral mechanical alignment may not be the ideal alignment in all patients and that malalignment does not necessarily lead to increased wear, at least in some type of implants[18-20].

This controversy about coronal alignment stimulated our interest in studying some of the remaining issues in further[21].

The first two introductory chapters of this doctoral thesis will define the parameters of coronal alignment and will state the hypotheses we wanted to prove during this scientific work.

Definitions

1. Coronal Alignment
   Coronal or frontal alignment is one of the three alignment planes of the knee and can be studied by 2D radiology with several measurements available to identify the different angles of lower limb alignment and component positioning. The coronal plane is the anteroposterior (AP) plane observed on radiographs.

2. Axis Deviation Terminology
   If the lower limb is bowed, it is called varus (Figure 1, left picture) and if the knees are knocked, it is called valgus (Figure 1, right picture).

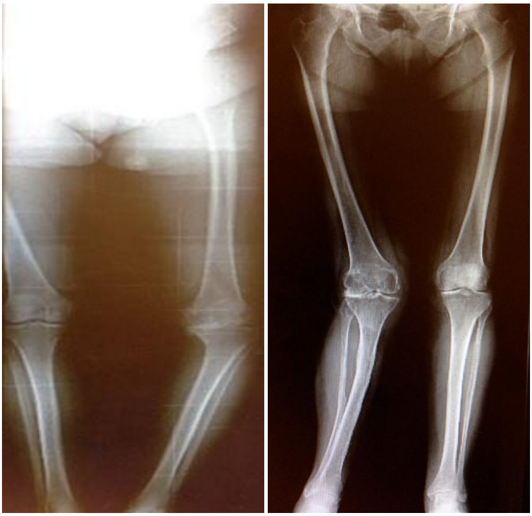


Figure 1 *shows on the left picture a left knee with an important varus deformity and on the right picture a right knee with an important valgus deformity, both identified on full leg standing radiographs.*

3. Anatomical Alignment
   The overall anatomical or physiological axis of the lower limb can be observed clinically (usually 6° of valgus compared to a vertical axis). It can also be measured on 2D radiographs as the angle between the anatomical axis of the femur (centre of femoral diaphysis extended distally) and the anatomical axis of the tibia (centre of tibial diaphysis extended proximally) (Figure 2). The mean angle for anatomical alignment is 6° of valgus[22,23].

Figure 2 *shows anatomical axes drawn on the right lower limb demonstrating anatomical alignment measured on a full leg standing radiograph.*

4. Mechanical Alignment

   The mechanical axis of the leg is a radiographic measurement that is determined by a line from the centre of the femoral head to the centre of the ankle joint[24]. The mechanical axis of the leg can be segmented into the femoral and tibial mechanical axis. The femoral mechanical axis runs from the centre of the femoral head to the intercondylar notch of the distal femur. The tibial mechanical axis runs from the centre of the proximal tibia to the centre of the ankle (Figure 3).

   The angle on the medial side between the femoral and tibial mechanical axis is called the hip–knee–ankle (HKA) angle[24]. The HKA angle represents the overall mechanical alignment of the leg in degrees.

   The neutral mechanical alignment axis is called 180° HKA but the axis can also be varus and expressed as a minus 180° value (for example, 6° of mechanical varus would be 174°) or it can be valgus and expressed as a plus 180° value (for example, 6° of mechanical valgus would be 186°).

***Figure 3** shows femoral and tibial mechanical axes drawn on right lower limb showing the HKA-angle on a full leg standing radiograph demonstrating varus alignment.*

5. Test-retest, intra- and interobserver reliability
   For obvious reasons there will be test-retest, intra- or inter-observer variability if the anatomical landmarks of the HKA-angle are chosen differently. For mechanical alignment, these values approximate ±1°, ±1° and ±1°, respectively[25]. Other sources of variability include the radiographic technique used, with significant differences when comparing CT and radiographic techniques of mechanical alignment measurements after TKA, because of the impact of rotation and load-bearing on limb alignment[26].

6. Load Bearing Axis
   The mechanical axis of the lower extremity ideally runs through the centre of the knee and can be described as the load-bearing axis (LBA) drawn from the centre of the hip to the centre of the ankle (Figure 4) on full leg standing radiographs[27]. The knee centre can than either be lateral from the LBA in case of varus deformity or medial from the LBA in case of valgus deformity. Historically, the aim of deformity correction in TKA has always been to bring the LBA under load-bearing conditions back to the centre of the knee or as close as possible. Today, a little more controversy exists about this topic.

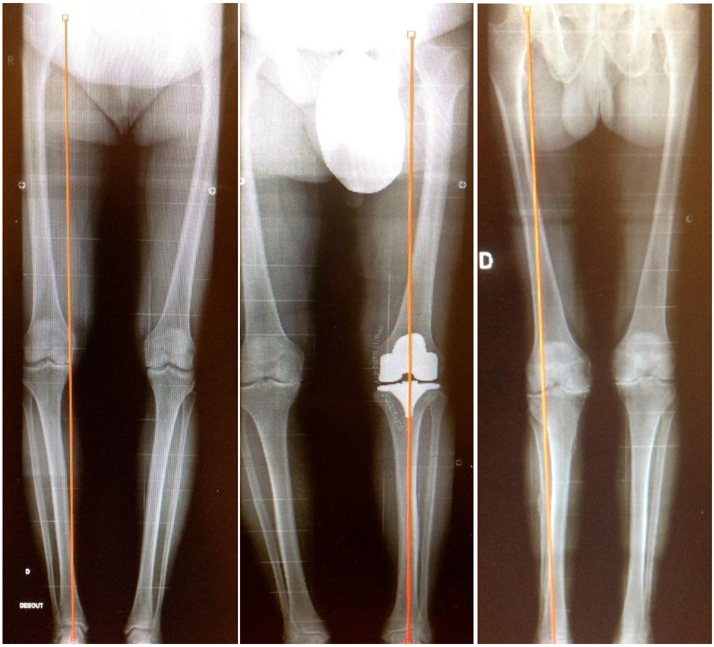


Figure 4 *on the left shows the load-bearing axis in a varus-aligned leg. The LBA is running medially from the knee centre. On the right figure the load-bearing axis is drawn for a valgus-aligned leg. The LBA is running laterally from the knee centre. The middle figure shows a neutral load-bearing axis after total knee arthroplasty of the left knee with the LBA in the centre of the operated knee.*

An important question might be if the load-bearing axis is the same under weight bearing or under non-weight bearing conditions?

Because of foot position, floor contact and the dynamics of the concave diseased compartment as well as the convex soft tissues, the LBA can change position under weight-bearing conditions[28]. According to this study, these changes are related to the amount of articular wear and the load-bearing axis. This is an important notice for the preoperative planning process and especially when patient-specific instruments are used[28].

7. Alignment and malalignment
   Alignment is the lower limb position of the leg as observed either clinically or radiographically. Ideally it should be 180° mechanical alignment or 6° of valgus anatomical alignment (left image of Figure 5).
   Malalignment is any deformity of the lower limb outside of the normal range (right image of Figure 5).
   For mechanical alignment, a range of ±3° is considered the normal range because of measurement variability[22,29] and therefore neutral mechanical lower limb alignment can be 178° to 182°. Outside of those limits, the alignment becomes varus mechanical alignment at 177° or less and valgus mechanical alignment at 183° or more.

Figure 5 *on the left shows a neutral mechanical alignment of the left knee and the figure on the right shows a left knee with mechanical malalignment in varus.*

8. Accuracy and precision

Accuracy is defined as the closeness of a measured value to the actual true value (an accepted reference value). It determines the capacity to reach the target value. It is a measurement with both true and consistent results. An accurate measurement has no systematic error and no random error. Accuracy comes as the combination of trueness and precision.

Trueness is defined as the closeness of an average measurement (arithmetic mean) to a true value, while accuracy is the closeness of a single measurement to the true value. Trueness is the estimate of the systematic error (Figure 6, ordinate).

Precision is defined as the closeness of two or more measurements to each other, so it measures the ability to consistently reproduce the same value. Precision is associated to the standard deviation as it's quantitative expression and is a description of random errors (Figure 6, abscissa). It is the estimate of the random error, which usually comes from unknown and unpredictable changes. Two important conditions of precision are repeatability and reproducibility describing the minimum and the maximum variability in results.

Error is defined as the difference between the measured value and the true value. This error can either be a systematic error or a random error. A systematic error, is a component of error that varies in a predictable way. A random error, is a component of error that varies in an unpredictable way.

Bias is estimated as the difference of the mean value of several measurements from the reference value. Bias is the total systematic error.

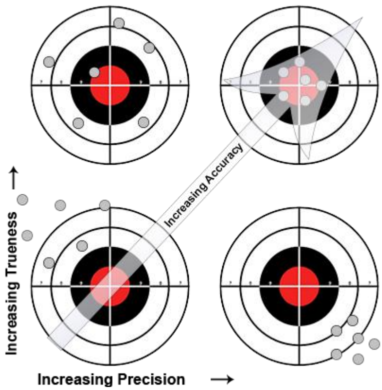


***Figure 6** shows increasing trueness on the ordinate and increasing precision on the abscissa. With increasing trueness and precision, accuracy will increase.*

Measurements of coronal alignment

The objective evaluation and measurement of coronal plane alignment asks for a radiological technique. This plane seems easily accessible since it is looking straight at us. Computer tomography has certainly the advantage of allowing a correction for rotation, but it is a measurement of alignment under non-weight bearing conditions. It also has the disadvantage of higher doses of irradiation for the patients (3.23 mSv). Therefore standing full leg radiographs are utilized more commonly, especially for the evaluation of knee components and lower limb alignment after knee arthroplasty[27,28].

Anatomical alignment can be analysed on short leg films if the distal femur and proximal tibia are partially shown. However, this makes it impossible to visualize any extra-articular deformity or bowing of the femur if they would be present, changing potentially the alignment completely. Short films are ideal for evaluating loosening and osteolysis as well as individual component alignment[30]. Combining both at distinct time points during the clinical follow-up of the implant can help the surgeon understand the case better. Especially, during the preoperative period and at one year after surgery an alignment analysis can be interesting. Standing radiographs will express more the dynamic aspect of the joint position at load-bearing[15]. Also at longer follow-up, the impact of progressive wear of polyethylene components changing the alignment combined with short films who will show the individual position of each component in the different planes of alignment (secondary displacement of components due to osteolysis and loosening).

Measurements of coronal deformity

Any deviation of neutral mechanical alignment, with an HKA angle smaller than 178° or larger than 182°, can be called a lower limb deformity. This deformity can either have its origin at the intra-articular level or at the extra-articular level.

The intra-articular deformity is related to wear of the cartilage and the observed HKA-angle can be constituted by the following formula (**Figure 7**):

$$\text{HKA angle} = mLDFA + MPTA + JLCA$$

With

mLDFA	mechanical Lateral Distal Femoral Angle
MPTA	Medial Proximal Tibial Angle
JLCA	Joint Line Congruency Angle

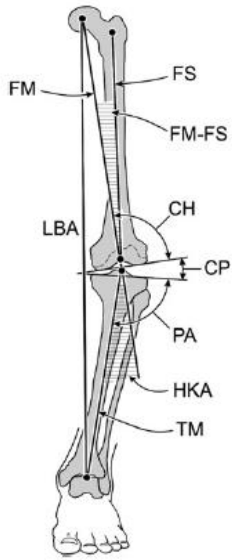
or

$$\text{HKA angle} = CHA + PA + CPA$$

With

CHA	Condylar Hip Angle
PA	Plateau Angle
CPA	Condylar Plateau Angle

The HKA-angle can be estimated by adding mLDFA+MPTA+JLCA or by adding the CHA+PA+CPA angles coming to a value higher or lower than 180°.



Legend

FM	Femoral Mechanical Axis
FS	Femoral Shaft Axis
FM-FS	Angle between FM and FS
LBA	Load Bearing Axis
CH	Condylar Hip Angle
CP	Condylar Plateau Angle
PA	Plateau Angle
HKA	Hip Knee Ankle Angle
TM	Tibial Mechanical Axis

***Figure 7** shows varus alignment of the left leg with the Load Bearing Axis (LBA) running medially of the knee centre and the deformity being expressed as CH Angle + P Angle + CP Angle, equalling a value lower than 180° HKA-angle.*
(Adapted from Sobczak S. 2012)

Any deformity can also have an extra-articular component with an apex of deformity at a distance from the articular surfaces (meta-or diaphyseal deformity). The potential of correction with an intra-articular osteotomy will depend on the distance of the extra-articular deformity from the joint line. The closer to the joint line the deformity is, the more it will need a larger correction inside the joint. If the needed correction breaches the collateral ligaments attachments, than an extra-articular correction is necessary[31].

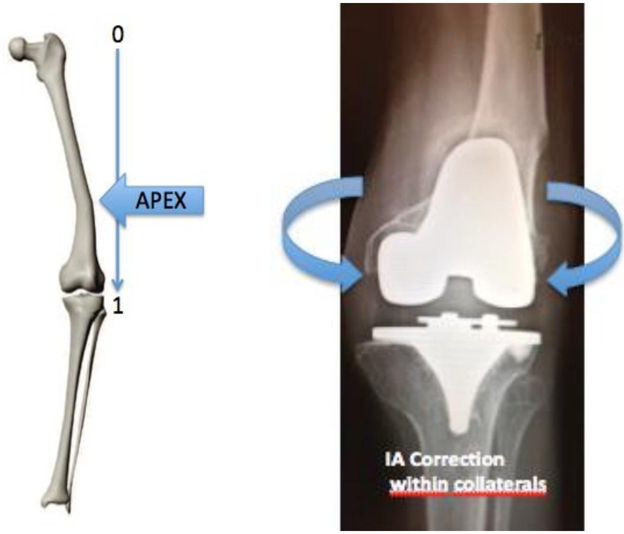


Figure 8 *shows on the left the apex of a distal deformity of the femur with a distance distribution of about 0.8 to the total length of femur. Figure 8 shows on the right a total knee arthroplasty with intra-articular correction of the extra-articular deformity within the boundaries of the collateral ligaments.*

Important intra-articular bony angles determining coronal limb alignment are

- Distal Lateral Femoral Angle: which is the distal angle of the femur (Figure 9). This angle can be measured against the mechanical axis (mLDFA) or against the anatomical axis (aLDFA) of the femur.

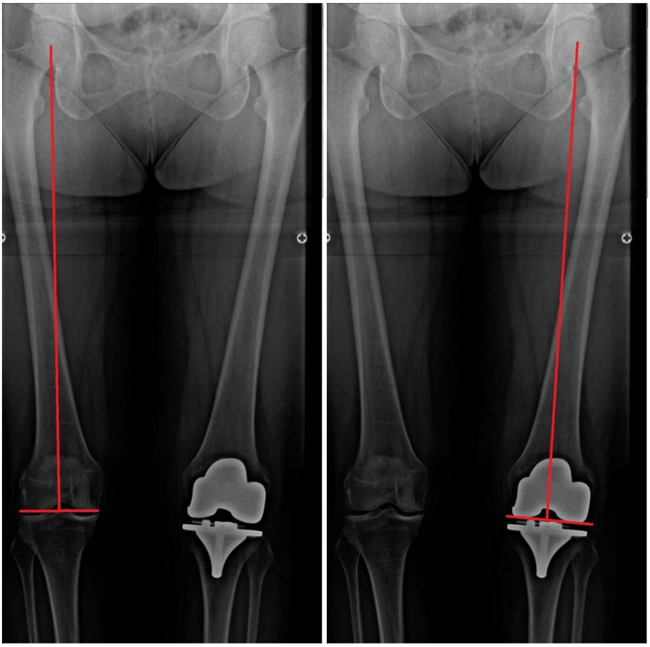


Figure 9 *on the left shows mLDFA measured on the right knee before surgery during deformity analysis. The image on the right shows the mLDFA after TKA of the left knee.*

- Medial Proximal Tibial Angle: which is the proximal angle of the tibia (Figure 10). This angle can be measured against the mechanical axis (mMPTA) or anatomical axis (aMPTA) of the tibia. The particularity of the tibia is that mechanical and anatomical axes in the coronal plane are quite similar and therefore one term, MPTA is usually utilized.

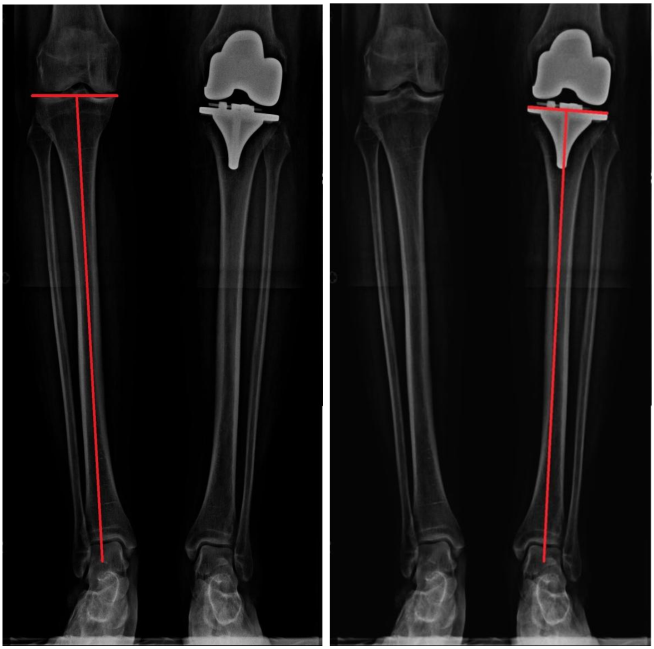


Figure 10 *on the left shows MPTA measurement of the right knee during preoperative deformity analysis. On the right side of the figure, the MPTA is measured after TKA of the left knee.*

- Joint Line Congruency Angle: which is the angle between the knee joint lines of the distal femur (LDFA) and the proximal tibia (MPTA) (Figure 11).
  It is sometimes also called Condylar Plateau (CP) angle. This angle shows the joint line opening on the convex side of the deformity and is an expression of convex side soft tissue laxity. It is open on the lateral side in the varus knee and open on the medial side in the valgus knee.

Figure 11 *shows on the left side a right knee with varus deformity and opening of the joint on the lateral or convex side. The lateral JLCA in varus deformity is usually 3°. On the right side a right knee is demonstrated with valgus deformity and medial or convex joint opening. The medial JLCA in valgus deformity is usually 2°.*

The shape of bones and the influence of degenerative disease processes with wear and tear on the bony geometry change alignment. When knee arthroplasty is performed, the knee components' individual alignment and the soft tissue balancing will influence the final alignment. Initially, the emphasis was on polyethylene survival and therefore neutral mechanical alignment was the generally accepted technique to allow equal load distribution over the entire polyethylene component. In more recent times, neutral lower limb alignment obtained by component positioning with non-anatomical joint positions lead to the controversy about the "right" alignment. The aim was no longer only longevity but optimal patient satisfaction[21]. A neutral mechanically aligned femoral component reduces the natural valgus of the femur and a neutral aligned tibial component reduces the natural varus of the tibia, changing the natural joint line obliquity, patellar tracking and potentially the parallel joint line position to the floor[21].

The challenge in the treatment of knee osteoarthritis lies in the conversion of a deformed and sometimes stiff joint knee joint into a well-functioning, well-aligned, mobile and stable joint through the implantation of different articulating components. These components need to be well positioned in all planes and reconstruct the normal anatomy as it was before the disease process took place. However, the surgeon needs to obtain this result within the soft tissue envelope created by a degenerative disease. Furthermore, the natural knee has a very complex anatomy with several ligaments and supporting structures like the meniscus and the articular cartilage with each their own conformity. The loss of one of those structures might lead to the development of OA according to a specific pattern. For example, after a lateral meniscectomy patients will develop posterolateral OA and after an anterior cruciate ligament rupture they might develop posteromedial OA. This slow degenerative process will influence the soft tissues over time and different ligaments might contract or loosen. Surgeons have to reconstruct the degenerative knee joint not with the same anatomic structures with the same elasticity and stability, but with several metal and polyethylene components, which each have their own 6 degrees of freedom in positioning. A multitude of combined errors is therefore in theory possible. A knee arthroplasty has to be adequately aligned according to frontal, sagittal and axial alignment principles. Axial alignment has been extensively studied and has always been considered the most difficult alignment to accurately obtain because the rotational landmarks (epicondyles) are more difficult to identify than the anatomical axes of the bones. Sagittal alignment is probably the least studied because of the absence of overall alignment analyses with lateral full leg radiographs. The individual component positions like slope and femoral flexion are easily studied on short films but these radiological studies don't necessarily give information about the lateral plane weight-bearing alignment. Finally, frontal or coronal alignment of the knee seems the most obvious, and probably therefore less appreciated. It is easily observed on simple radiographs and presents itself easily for angle measurements. However since 2010, when surgeons started realizing that polyethylene wear became less of an issue and functional outcome more of a need, the topic of coronal alignment came back into the spotlight. Different types of coronal alignment can be observed after knee arthroplasty leading to a lot of discussion among clinicians about the "right" type of coronal alignment.

Different types of alignment in total knee arthroplasty

1. Neutral Mechanical Alignment

According to this concept, which was first described by Insall et al.[32], the implant is aligned in a neutral HKA position, which ideally would be 180°. Both the femoral and tibial component are aligned perpendicularly to their mechanical axis and the CP Angle or JLC angle should be 0° due to soft tissue release on the convex side of the deformity (Figure 12). On average during surgery, the LDFA changes from 9° to 6° of valgus and the MPTA changes from 3° of varus to 0°. The natural joint line obliquity is therefore sacrificed to obtain neutral mechanical alignment[33].

Figure 12 *shows implant positioning according to mechanical alignment principles.*

2. Anatomical Alignment
   This concept was originally proposed by Hungerford et al.[34]. The basic concept is that the optimal component position must anatomically restore the joint line. The implant is aligned according to an oblique coronal joint line position (Figure 13). The LDFA is in a 9° valgus position and the MPTA in a 3° varus position. This allows both components to be aligned according to the natural joint line[33].

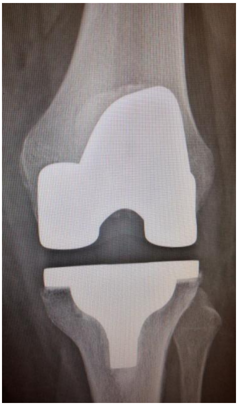


Figure 13 *shows implant according to anatomical alignment principles with tibia in 3° of varus and femur in 9° of valgus with neutral rotation of the femoral component.*

3. Kinematical Alignment
   This concept is based on the work from Hollister et al.[35]. It has been popularized by Howell et al.[36,37]. The implant is recreating the kinematical axis of the natural knee and restoring the surfaces that changed because of wear. Alignment is of less relevance and might remain varus or valgus after surgery.

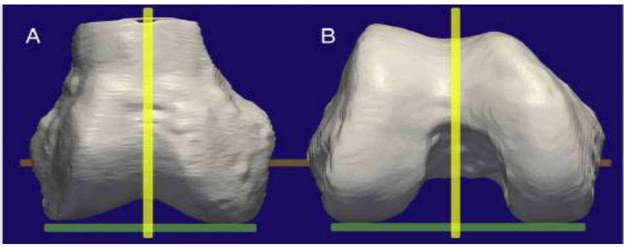


Figure 14 *shows the axes determined for kinematical alignment.*
(Courtesy of S. Howell)

4. Constitutional Alignment
   This concept was introduced by Bellemans et al.[38,39] after the previous work of Hsu .[40] and Moreland et al.[41]. All of these three authors observed that the mean mechanical alignment of a Caucasian population is 178° and not 180°. Bellemans had noted that 32% of males and 17% of females have constitutional varus (Figure 15) with their native mechanical alignment being varus alignment[38]. Therefore a correction to 180° might be an overcorrection leading to dissatisfaction for this type of patient.

Figure 15 *shows constitutional varus of 2° with an HKA-angle of 178°.*

When selecting coronal alignment as the topic for this doctoral thesis it was decided to give priority to this alignment without underestimating the importance of the other two planes and with respect of the impact of each of the three alignment planes individually on the other plane[4-10]. However, for study purposes and because of the limited resources a clinical researcher has, the observations were made based on our daily clinical practice and the observed needs to treat our patients better.
The trigger of this project was an editorial we wrote in 2013 stating that there were still more questions about alignment than answers[21]. Furthermore a study about the huge interest of surgeons in patient-specific instruments[42] without available peer-reviewed data at that time, made us reflect about the importance of accuracy, the ease of adoption of new technologies in our business as well as the options to study outcome in case of better alignment.

Alignment in Partial Knee Arthroplasty

Whenever partial replacement of a joint is possible, surgeon and patient can discuss this surgical option[43]. In patellofemoral arthroplasty lower limb alignment is not influenced because no cuts are performed on the level of the femorotibial bones.
In partial knee replacement of the medial or lateral compartment undercorrection is proposed to avoid disease progression in the other compartment[43]. Therefore understanding the constitutional alignment of the patient might be important[20,21,38].

Partial knee replacement is a specific area within arthroplasty surgery. Patient selection is much more crucial and the potential choices ask for balancing the risks and benefits[43]. When we studied the different patterns of wear in degenerative joint disease, we learned to appreciate the factor alignment into the equation[44].
Anteromedial OA in the presence of overall valgus alignment should make the surgeon think twice about the choice of UKA versus TKA. But in the same way understanding constitutional varus or valgus alignment should help us feel more reassured about the postoperative correction that is obtained after resurfacing surgery. A lateral UKA ending up with a 184° HKA-angle is probably a knee restored to its natural and constitutional valgus alignment and not necessarily a badly aligned knee. The technical challenges in UKA are much more important since no error in alignment of components or bone cuts is allowed, leading much earlier to implant failure and revision[45]. The clinical outcome that can be obtained as well as the lower risk of morbidity and mortality should not be underestimated whenever the choice of implant should be made[46].
Coronal alignment has for many years been discussed for medial unicompartmental components. The discussion between mechanical alignment and anatomical alignment of the tibial component is still going on among resurfacing knee surgeons[47]. Coronal alignment has, to the best of our knowledge, rarely been analyzed for patellofemoral arthroplasty. During the process of coronal alignment studies we observed the impact of this alignment on the patellar tracking for example, which was always attributed to axial alignment primarily[48]. This observation is just another proof of how all three alignment planes are interlinked.

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Alignment in Total Knee Arthroplasty: Analysis of Surgical Accuracy

Chapter II: *Aims and hypotheses*

The understanding of native, diseased, and replaced knees has significantly improved in recent years. Combined with recent developments in technology, such as computer navigation and patient specific instrumentation, this has led to further investigations about coronal alignment[1-6]. Long-held tenets have been challenged.

The major points of investigation performed by other authors inspiring us to further research can be summarized as follows:

1. Concept of constitutional varus
   Bellemans et al. performed an epidemiologic study on a group of Caucasian subjects and observed that this segment of the population has a 178° mechanical alignment of the lower limb. This concept suggests that a correction of varus deformity to 178° (=> slight varus) might achieve better functional outcome than a 180° (=> neutral position) correction[5]. Several papers have since shown that undercorrection leads to a better outcome[7-10]. Nothing is known today, to the best of our knowledge, about undercorrection in knees with valgus alignment.

2. Undercorrection does not lead to increased wear
   Neutral mechanical alignment has been considered an absolute necessity to avoid wear of components[3]. With the arrival of new materials and better polyethylene bearings this became less important. Several recent studies have shown that lower limbs remaining in overall varus do not necessarily lead to increased wear of the polyethylene and loosening of the implant[1].

3. Joint line parallel to the floor
   Victor et al. looked at the orientation of the joint line relative to the floor in bipedal stance and found that the joint line appears to maintain its parallelism to the floor, irrespective of the magnitude of non-arthritic varus deformity[11].

   The concepts of coronal alignment have evolved since we wrote our editorial in 2013[12] and we have, therefore, chosen this topic for further study.

   The overall proposition of this doctoral thesis is as follows:

   Coronal plane alignment in total knee arthroplasty is an area of significance that needs further development. Additional efforts will be required to determine individually optimized coronal plane alignment and to improve accuracy of total knee arthroplasty instrumentation to facilitate such alignment.

More specifically, the hypotheses of this doctoral thesis are:

1. *Surgeons currently do not evaluate preoperative and postoperative alignment with full leg radiographs and the principles of constitutional alignment are not yet commonly applied in their daily practice today.*

   This hypothesis will be tested by a survey of knee surgeons. We will ask them about their attitude towards coronal alignment and the option of keeping an implant postoperatively in varus alignment.

2. *Substantial deformity in the coronal plane cannot only be corrected by LDFA and MPTA corrections.*

   This hypothesis will be tested by a radiographic study of lower limb alignment, pre- and postoperatively, in a group of patients with substantial deformities. Primary TKA was performed in 51 patients with substantial preoperative deformities (>10° mechanical deformity). A new semantic classification for deformity description is proposed after this study.

3. *Bone morphotypes of the varus and valgus knee.*

   This hypothesis states that bone morphology in varus and valgus deformity is different. The observed measurements explain deformity measured as HKA-angle. Perpendicular cuts to mechanical axes lead to lateral distal joint line overstuffing in the valgus knee and therefore adequate soft tissue balancing is required. In the valgus knee constitutional valgus should be considered similar to constitutional varus.

4. *Varus knee deformity needs a combined clinical and radiological classification for better understanding of pathology.*

   This hypothesis states that varus deformity can either be intra-articular or extra-articular. Intra-articular deformities can be correctable or fixed. In fixed deformities the status of the lateral ligament is taken into account. Extra-articular deformity can be metaphyseal or diaphyseal and the possibility for intra-articular correction will depend on the degree of deformity and its distance from the joint. This new classification allows for better definition of varus deformity, which can help surgeons during preoperative planning, particularly with their choice of implant and potentially the degree of constraint.

5. *Accuracy, precision and trueness for total knee arthroplasty with conventional instruments.*

   This hypothesis states that we can define the objective of accuracy in total knee arthroplasty by looking at neutral aligned persons and at the mean of overall alignment. The ability to obtain trueness and precision is calculated for conventional instrumentation after total knee arthroplasty.

6. *Surgical accuracy might not be increased with Patient Specific Instruments (PSI).*

   This hypothesis will be tested with a systematic review and meta-analysis of alignment-related studies, including randomised controlled trials (RCTs) and cohort studies, to examine the effect of PSI on radiographic outcomes after PSI-TKA versus conventional TKA, specifically considering the overall mechanical axis and alignment of the individual components in the coronal, sagittal and axial planes.

7. *Coronal alignment is also important in implants that do not have a distal femoral cut and which are not total knee arthroplasties.*

   This hypothesis will be tested with a radiographic analysis, on standing full leg radiographs, of the distal femoral alignment of patellofemoral arthroplasty (PFA). The way in which the trochlear implant's transitional edges articulate with the condylar cartilage determines coronal alignment or varus-valgus position in PFA. Variations in condylar anatomy can affect the Q-angle of the PF joint, although it has no influence over the axis of the lower limb after PFA.

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Alignment in Total Knee Arthroplasty: Analysis of Surgical Accuracy

Chapter III: What is the current opinion of surgeons about coronal alignment today?

Introduction

In its infancy, total knee arthroplasty (TKA) was performed by linking the femur and tibia with a hinged joint[1]. Advances in the understanding of anatomy and biomechanics have led to the introduction of the unconstrained total condylar knee. The surgeon's objective was to give the suboptimal materials the ability to survive for as long as possible by optimizing their alignment, mobility and stability. TKA was initially performed for patients with advanced degenerative disease, and pain relief was the main expected outcome. Lifestyle expectations have become raised over time, and this has prompted a huge development of activity within the industry over the last ten years. The increasing number of TKAs being performed each year and competition between hospitals has resulted in orthopaedic suppliers pushing the boundaries of innovation. However, the proportion of patients who are dissatisfied following TKA is still as high as 20-30% and this has re-ignited the debate about how components should be aligned (anatomical vs mechanical alignment)[1,2]. There has been a consensus among TKA practitioners that the ideal HKA-angle is 180° and that the implant's longevity is dependent on its alignment. It was thought that outliers would result in failure at an early stage and increase patient dissatisfaction,[3,4] but research findings that contradicted this theory started to appear in 2010. This literature argued that residual varus alignment of the lower limb was not the cause of implant failure, and that undercorrection of a varus deformity might even lead to improved outcomes[1]. A possible explanation for this was the discovery that varus could be the mean alignment of the Caucasian population, and that mechanical undercorrection would merely replicate their pre-disease or constitutional alignment[5].
To assess the current opinions of a substantial and geographically diversified group of knee surgeons, we conducted a survey with regard to their ideas about coronal alignment and their ideas about keeping an implant in varus alignment.

What is the current opinion of surgeons about coronal alignment today?
Adapted from: Thienpont E, Cornu O, Bellemans J, Victor J. Current opinions about coronal plane alignment in total knee arthroplasty: A survey article.
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Abstract

Purpose: To survey an audience of international knee surgeons about their current opinions on the analysis of coronal knee alignment and their objectives for postoperative alignment in total knee arthroplasty.
Methods: Survey of 300 surgeons from 32 different countries with an audience response system allowing three possible answers being either a positive or negative answer or an abstention.
Results: Surveyed surgeons perform rarely preoperative and postoperative full leg radiographs and evaluate radiological outcomes more with short films. The main trend in this survey was towards neutral mechanical alignment, however varus alignment is acceptable in constitutional varus patients. This residual varus should be obtained through a femoral varus cut rather than a tibial varus cut. The valgus knee can remain in slight valgus but most of the correction will be performed at the femoral level. The main objective of postoperative alignment in TKA is a joint line parallel to the floor and a central load-bearing axis through the centre of the arthroplasty. Surgeons prefer unicompartmental arthroplasty more for themselves than for their patients in case of medial bone on bone arthritis.
Conclusions: Neutral mechanical axis with a joint line parallel to the floor and a centrally running load bearing axis remains the central scope of the surveyed surgeons. Because of the literature on residual varus it becomes more acceptable for the orthopaedic community to accept this type of outlier before aiming at a surgical correction.

Introduction

Alignment or the relative position of the femoral bone compared to the tibial bone is an important issue in total knee arthroplasty (TKA)[6]. Alignment in the coronal plane can be expressed as anatomical alignment, measuring the angle between the femoral anatomical axis of the bone and the tibial anatomical axis of the bone (Figure 1) or as an angle referenced of the vertical axis running through the symphysis of the pubis (Figure 2). This angle is usually ±6° of valgus[2,7,8]. The same position of the bones or implants can also be evaluated by the criteria of mechanical alignment (Figure 1). In that case the angle between the centre of the Hip, Knee and Ankle (HKA) is measured as the HKA-angle of the lower limb[2,8,9]. This angle should be 180° aligning the hip with the ankle creating a mechanically stable situation for the lower limb[2,8,10].
The classic axiom in TKA surgery was that the HKA-angle needs to be 180° and that the longevity of the implant is directly related to its alignment. Outliers would lead to early failure and potentially less satisfied patients[3,4]. However anno 2010 literature reports appeared, showing that residual varus alignment of the lower limb was not evidently leading to failure of the implant and that undercorrection of a varus deformity could even result in better functional results[11-14].

This was potentially explained by the finding that the overall mean alignment of the Caucasian population might be varus anyway. Therefore mechanical undercorrection would only align them as before the disease process[5,15]. Alignment can be measured according to the Knee Society Radiological Score on short films[16] or it can be evaluated on full leg standing radiographs[17,18]. The advantage of this second option is that the position of the implants is evaluated in a load-bearing position and that the mechanical alignment can be measured as degrees deviating from the neutral 180° axis[8,9,19].
The aim of this study was to survey the current opinions of a substantial and geographically diversified group of knee surgeons, attending a knee meeting, on their ideas about coronal alignment and especially the option of keeping an implant post-operatively in varus alignment.


Figure 1 *on the left shows on the right leg the load-bearing axis and on the left leg the anatomical axes of the lower limb as drawn on full leg standing radiographs.*

Figure 2 *on the right shows the vertical axis running down the symphysis pubis and the mechanical axis drawn on the left lower limb.*

Materials and methods

During the 'Recent Advances in Knee Surgery' meeting in September 2013 in Prague, Czech Republic the attending surgeons were surveyed about their opinions on coronal alignment of the lower limb and knee arthroplasty surgery. From the 650 attendees from 32 different countries, the opinion of 300 surgeons was taken by an Audience Response System (ARS). The surveyed group consisted of 12% orthopaedic residents in their senior year having expressed a clear knee interest, 32% general orthopaedic

surgeons, 24% knee surgeons (sports medicine and knee arthroplasty) and 32% knee and hip arthroplasty surgeons.
The questions were presented on screen, read by the moderator and the possible answers were “I do”, “I don’t” or abstention of an answer. After each question the audience had 15 seconds to answer and during that period only one answer was possible for each respondent. The results of the voting were given only at the end of the session to avoid influencing the audience on the next question by the response on the previous question.

Demographics of the surveyed population
A first multiple choice question was asked about the surgical activity of the survey population with twenty-one percent of surveyed surgeons replying that they performed less than 30 TKA/year, 23% between 30 and 49 TKA/year, 28% between 50 and 99 TKA/year, 12% between 100 and 149 TKA/year, 8% between 150 and 200 TKA/year and finally 8% more than 200 TKA/year. Two percent of surveyed surgeons performed only sports medicine and 14% only knee arthroplasty, 41% sports medicine and knee arthroplasty equally, 11% performed more sports medicine than arthroplasty and 32% more arthroplasty than sports medicine.
Related to their arthroplasty activity the survey also asked about their practice distribution of primary versus revision arthroplasty. Thirty-nine percent of surgeons performed 95% of primary TKA versus 5% of revision, 23% had a 90% versus 10% distribution, 11% had a 80% versus 20% and 5% a 70% versus 30% activity with finally 11% of surgeons having a 50/50 distribution of primary versus revision.

Results

Since the above questions about their surgical profile and activity could be considered as potentially threatening[20], the presentations of the session were given before a new series of questions were proposed to the audience. The following questions were presented with the AR System:
The question was asked if a surgeon would like for himself a unicompartmental knee arthroplasty (UKA) or a TKA if he presented with isolated anteromedial arthritis while showing a typical radiograph of bone on bone medial arthritis and explaining the knee had normal stability. Of the replying surgeons 87% preferred an UKA for their own knee. However when for the same radiographic and clinical situation the question was asked whether they would offer an UKA to their own patient, only 78% answered yes. So about 9% of surgeons changed opinion on the appropriate treatment for any typical patient compared to them.
A survey was furthermore performed on their opinions about coronal alignment with “I do” and “I don’t” as well as abstention answers. The results are given in Table I. When asked about a fixed anatomical-mechanical angle (AMA-angle) of the femur; 27% replied it was always 5°, 28% answered it was 6° and 11% answered it was 7°. Twenty-eight percent replied the angle is patient specific and should be measured on each case and 6% had no opinion.

Survey questions and answer options	I do %	I do not %	No opinion %
Do you perform preoperative full leg radiographs prior to TKA?	49	13	38
Do you perform postoperative full leg radiographs after TKA?	19	54	27
I believe short film radiographs give enough information for adequate preoperative planning prior to TKA?	32	68	0
I believe short film radiographs give enough information for adequate postoperative evaluation after TKA?	54	46	0
I always measure the preoperative HKA-angle before TKA?	49	51	0
I always measure the postoperative HKA-angle after TKA?	26	71	3
I believe a varus knee should remain in varus postoperatively?	40	58	2
I can see preoperatively who had constitutional varus and needs remaining varus after surgery?	46	50	4
To keep a TKA in varus, I perform a varus cut on the tibia?	16	78	6
To keep a TKA in varus, I perform a varus cut on the femur?	36	58	6
I believe a 180° +/- 3° HKA-angle is important for good functional results?	50	40	10
I believe more than 3° of an alignment outlier is acceptable in TKA?	50	50	0
I believe a valgus knee should remain in valgus?	54	43	3
I believe valgus should remain on the femoral side in the valgus knee?	14	83	3
I believe valgus should remain on the tibial side in the valgus knee?	15	80	5
I believe the femur should be cut in more varus in the valgus knee?	60	36	4
I believe the primary goal in TKA alignment is to have a joint line parallel to the floor?	72	22	6
I believe it is more important to have a central load bearing axis than a 180° HKA-angle after TKA?	63	19	18
I believe mechanical alignment of the lower limb is more important than anatomical alignment after TKA?	77	20	3
I believe the anatomical alignment after TKA should be 6° of valgus from a vertical axis?	57	33	10

Discussion

The most important finding of this survey study was that the opinions on coronal alignment are still divided in the orthopaedic community. The principles of residual postoperative varus alignment after TKA are well known, but not generally accepted by everyone. The concept of a joint line parallel to the floor seems more accepted. Surgeons overall prefer neutral mechanical alignment but abstain of strict radiological postoperative evaluations.
Another interesting finding of this survey was that surgeons seem to prefer a unicompartmental arthroplasty for themselves when confronted with isolated bone on bone anteromedial osteoarthritis of the knee. However about 9% of surgeons would treat their patient differently with a TKA.
Alghamdi et al. proved the importance of preoperative full leg radiographs showing that many patients, especially with valgus deformity present with extra-articular deformities that are difficult to predict or evaluate on short film radiographs[21]. This survey showed that surgeons performed in about 50% of cases preoperative full leg radiographs but only 20% used that technique to evaluate their postoperative radiological alignment and 26% would measure their result as an HKA-angle. This finding clearly shows that the importance of evaluating alignment with full leg standing radiographs should be further analyzed. It should also be proven that alignment is related to clinical outcome and wear so that the cost of the radiographic analysis can have some consequences in the prevention of wear or in obtaining better outcomes[3,22].
Recent literature on alignment reconfirmed the findings of Hsu et al.[23] and Moreland et al.[17] that the overall coronal alignment of the population is not neutral but rather varus. Bellemans et al. introduced the principle of constitutional varus[5]. A majority of the surveyed surgeons believed a neutral mechanical axis should be the aim in the varus knee (58%) and only 46% thought they were able to identify which patient has or had constitutional varus before the disease process took place. In the survey group only a slight minority (16%) was ready to cut the tibia in varus and aim for anatomical or kinematical alignment[24-26]. The principles of anatomical and kinematic alignment are of growing interest nowadays. The majority (58%) would keep the femur in varus if that were their ambition for postoperative alignment. A femoral component in varus is however in contrast to the concept of anatomical alignment, where the distal femur should be in relative valgus[24,25].
Parratte et al. showed that for one particular surgeon (Dr. Rand from the Mayo Clinic, Rochester, US) neutral mechanical axis was not determining for longevity of the implants he used (Kinematic Condylar II, PFC and Genesis)[13]. And several authors showed that the functional outcome was better with remaining varus after correction of preoperative varus alignment with TKA[11,27,28]. A straight mechanical axis of 180° seemed important for good functional results for 50% of surveyed surgeons and the same amount thought outliers of more than 3° are unacceptable after TKA. Several authors showed however that the anatomy of the varus patient often leads already to undercorrection and that therefore a neutral mechanical axis should be the initial objective for a TKA[4,9,29-31].
Fifty-four percent of surgeons thought a valgus knee might remain in some valgus (< 184°) after TKA[3]. The majority corrects the femoral valgus however with an adapted varus cut on the femur, aiming at a correction of the Anatomical-Mechanical femoral angle lower than measured on the full leg radiographs.

A strong majority (72%) estimated that a joint line parallel to the floor was an important objective after TKA as well as having a central load-bearing axis running through the center of the knee prosthesis (63%). The joint line has been proven to be parallel to the floor in normal knees and knees with constitutional varus[7,15].
Finally, 77% of surveyed surgeons estimated that mechanical alignment was more important than anatomical or kinematical alignment[26,32]. Howell et al., showing good clinical results for patients, have extensively studied the concept of kinematical alignment, but according to this survey study this concept is not yet popular in the orthopaedic community[24,25]. The treatment of bone on bone medial compartment osteoarthritis remains a controversial topic. When surgeons were offered the choice of UKA versus TKA, they preferred UKA much more for themselves than for their patients. This confirms how the option of UKA still remains uncertain for surgeons[33]. The question whether patients will prefer survival over function is not solved yet[14].
A weakness of this study is the intrinsic problems of a survey study. Not all surgeons attending the meeting were surveyed. There is therefore a selection bias by the surgeons who preferred to use the audience response system. Furthermore there is always a suggestion in the question and the response time doesn't always allow sufficient reflexion about the question. Questions can be knowledge based or attitude based as in this survey. Often answers are impulsive and straightforward. The advantage of the weaknesses is that the answers are straight and reflect well the opinions of the surveyed surgeons. The authors also tried to balance the questions by separating "threatening" questions like (e.g. how many TKA did you perform last year?) from the actual survey with a break. The scientific presentations were used to create a time period between both sections of questions. Despite that most questions were closed-ended a "no opinion" option was offered as a further category of closed-response. Since this was an "opinion" survey the questions were well designed using the "I do/ I do not" format and making them "non-elliptical". General questions preceded specific questions and the number of questions was limited to avoid lower response rates[20].

Conclusion

Mechanical alignment of the knee is estimated as highly important by surveyed surgeons. Their primary ambitions are a joint line parallel to the floor and a centrally running load bearing axis. Despite of these strong opinions about alignment only a minority of surgeons evaluates his surgical result with postoperative full leg radiographs and HKA-angle measurements.
Surgeons with medial bone on bone arthritis prefer unicompartmental arthroplasty more for themselves than for their patients.

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Alignment in Total Knee Arthroplasty: Analysis of Surgical Accuracy

Chapter IV: Is substantial coronal alignment correctable with conventional instrumentation?

Introduction

A successful total knee arthroplasty (TKA) produces a stable, well-aligned joint accompanied by long-term results, patient satisfaction[1], and implant survival[2-4]. The restoration of alignment is dependent on accurate implant positioning and soft tissue balancing[5-10]. In the evaluation of TKA alignment, knees with a significant degree of deformity are particularly challenging, and it is debatable whether knees with severe deformity can be consistently and successfully treated[11]. Factors that influence the outcome of TKA in knees with severe deformity include the balancing of soft tissue and the nature of the deformity[1], with valgus and varus knees presenting their own difficulties.

We previously reported on a unique surgical approach in knees with substantial deformity using a primary posterior stabilized (PS) implant with minimally invasive surgery that provided shorter hospitalization, reduced pain, and quicker return of function[12-14]. Specifically, in the study, knees with substantial preoperative deformities (>10° mechanical deformity) were operated on via a far medial subvastus approach combined with a PS implant and soft tissue release performed with a piecrust needling technique[15]. Leaving the soft tissue sleeve intact was thought to allow easier soft tissue balancing and the use of the Vanguard implant (Biomet, Warsaw, IN, US) with its variability in sizes would also avoid constraints associated with a single size implant.

Despite devising a surgical approach that could provide better surgical outcomes for knees with severe deformities, we found that comparisons of outcomes across studies were difficult given the varied definitions of lower limb alignment[16]. Upon analysis, studies differed in mechanical and anatomical alignment measurements. Furthermore, in some studies, alignment was compared to the vertical axis with a wide range of normality depending of the author[16]. We therefore developed a new classification according to different degrees of severity. While common mechanical deformity is classified as 4° to 10° in this newly defined classification system, substantial deformity ranges from 11° to 20°, also offering a new terminology for important (21°-30°) and extreme deformities (>30°) when deformity is beyond the most frequently observed range of 3° to 20°[17]. Utilizing a standardized classification of deformity provides a consistent tool against which to measure alignment in the coronal, sagittal, and axial planes.

Is substantial coronal alignment correctable with conventional instrumentation?
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Abstract

Purpose: Although advocated for severe varus and valgus deformities, constrained implant designs are associated with a number of disadvantages in total knee arthroplasty (TKA). Combining a minimally invasive surgical approach with an interchangeable posterior stabilized (PS) implant design may allow adequate soft tissue balancing with a minimal amount of constraint and without residual instability.
Methods: Retrospectively 51 patients operated with the minimally invasive far medial subvastus approach for severe valgus or varus deformity who underwent primary TKA with an interchangeable PS implant (Vanguard, Biomet Inc., Warsaw IN, US) between 2009 and 2013 were examined. Soft tissue release was performed using a piecrust needling technique. Preoperative alignment and surgical parameters were collected for all patients. All patients underwent preoperative and follow-up radiographic assessment, and completed a battery of clinical assessments.
Results: All procedures were performed successfully, with alignment improving from a preoperative mean (SD) varus deformity of 165° (3º) and a mean (SD) valgus deformity of 196° (4.5º) to an overall mean (SD) postoperative mechanical alignment of 179.5° (3.0º). Ten patients had postoperative varus, while three patients had a postoperative valgus deviation from neutral alignment >3º. The mean change in joint line position in extension was -0.0±0.6 mm. Clinical scores at final follow-up were excellent.
Conclusions: Good TKA outcomes can be achieved in patients with substantial varus or valgus deformities using a combination of a minimally invasive far medial subvastus approach, interchangeable PS implants and soft tissue release with a piecrust needling technique.

Introduction

A stable and well-aligned joint is one of the primary goals of total knee arthroplasty (TKA) and is important for successful long-term clinical outcomes and patient satisfaction[1], as well as implant survivorship[2-4]. Central to this is the restoration of limb alignment by accurate implant positioning and soft tissue balancing[5-11]. These challenges are magnified in TKA patients with severe deformity, particularly if the aim is to correct the deformity while balancing the soft tissues so as to use the least amount of constraint[11]. The nature of preoperative deformity also differs from patient to patient[1], and valgus and varus knees present their own particular challenges. It has consequently been questioned whether it is even possible to predictably and successfully correct extreme deformity in a large number of cases[11].
Combining a primary posterior stabilized (PS) implant with minimally invasive surgery (MIS) offers several potential benefits, as MIS is associated with shorter hospitalization, reduced pain and more rapid return of function[12-14]. The surgical approach can have an important influence on the soft tissue balancing. A medial collateral ligament (MCL)-sparing far medial subvastus approach in MIS TKA, was previously described with good

surgical outcomes and no radiological malalignment[18]. However, there are no results reported in literature of this surgical approach in patients presenting with substantial preoperative deformities.
For the current study, primary TKA was performed in 51 patients with substantial preoperative deformities (>10° mechanical deformity), in which the far medial subvastus approach was combined with a PS implant and soft tissues release performed with a piecrust needling technique[15]. The hypothesis was that leaving the soft tissue sleeve intact would allow easier soft tissue balancing and that the use of the Vanguard (Biomet, Warsaw, US) implant, which allows full interchangeability of sizes, would avoid the use of more constraint implants. Furthermore, the radiological and clinical outcome of these patients operated on with primary PS components were evaluated.

Materials and methods

Fifty-one patients (53 knees) with a fixed preoperative valgus or varus deformity who had undergone primary TKA for primary osteoarthritis between 2009 and 2013 performed by a single surgeon (ET) were invited to participate in a retrospective study. All but seven patients (seven knee) consented to participate in the study, giving a population of 44 patients (46 knees). Seven patients were not included because 1 died, 3 lived in another country and 3 were not able to come back to the hospital for clinical and radiological examination. All living patients were contacted by phone, as well as the family of the deceased patient. All were doing well and did not have symptoms of pain or instability and the deceased patient had not been revised before his death.
The mean (SD) age of the study population at the time of the surgery was 74.0 (9) years with 36 (70%) women and 15 (30%) men. Mean (SD) BMI was 31.5 (6) kg/m2. The mean (SD) follow-up time was 3 (2) years. Eight patients (18%) developed arthritis post open meniscectomy. None of the patients had a history of previous fracture or osteotomy.
HKA angles were obtained from radiographic anteroposterior full leg views of the lower extremity, with the patient standing in a weight bearing position. Substantial deformity was defined as an angle of more than 10 degrees of deviation on the neutral mechanical axis hip-knee-angle (HKA) measurement (<170° or > 190° HKA-angle)[19].

Surgical technique
All patients were operated by the same surgeon (ET), with staged bilateral knee replacement performed in two patients. A minimally invasive far medial subvastus approach[18,20] was used in both valgus and varus deformities. A measured resection with a femur-first technique was performed. The level of resection was dependent on the deformity and the stability of the knee in extension. Massive valgus deformity associated with hyperextension/hyperlaxity usually requires a reduced depth of resection of the femur[21,22], whereas varus with fixed flexion deformity often requires a deeper tibial resection depth to compensate for the eroded tibial bone and sometimes a more proximal femoral resection to obtain full extension. Another technique to ameliorate a deep posteromedial defect is to reduce the size of the tibial tray and lateralize the tibial component slightly, while resecting the overhung medial tibial bone (tibial reduction osteotomy)[23]. Deeper resection depth in the tibia during TKA leads to reduced surface area at the tibial plateau, in which case the implantation of a smaller tibia, is sometimes required due to the smaller surface of the underlying bone[24]. In case of a tibial reduction osteotomy, care was taken that there was enough bony support for the tibial baseplate.

Alignment was confirmed with an extramedullary guide on the tibial side and an intramedullary guide on the femoral side. In patients with substantial varus deformity, the deep fibres of the MCL were released from the proximal tibia within the soft tissue sleeve. Soft tissue releases were performed using a needling technique[25], while the assistant applied valgus force to the leg. If necessary, the posterior oblique ligament, pes anserinus and/or the semimembranosus tendon were also released. In the knees with valgus deformity, release of the iliotibial band was performed via pie-crusting with a needle[21]. If required, additional release of the lateral collateral ligament, popliteus tendon and posterolateral capsule was carried out with great care, as there is a risk of posterolateral flexion gap instability, which necessitates the use of a constrained condylar prosthesis design[26]. Ligament balancing was performed with the trial implants in place.
All patients received a cemented Vanguard PS knee (Biomet Inc., Warsaw, IN, US). No patients received a Condylar Constraint Knee or hinge design during the time period of the study. Postoperative rehabilitation consisted of immediate weight-bearing and mobilization with the help of a physiotherapist. Full weight bearing was allowed as soon as the patient was able to perform a straight-leg raise.

Assessments
Clinical assessment was carried out using the Knee Society (KSS) clinical rating system[27]. In addition, the patient-reported Knee Injury and Osteoarthritis Outcome Score (KOOS)[28] and the Forgotten Joint Score (FJS-12)[29,30] were administered at the final postoperative clinical evaluation. Postoperatively, pain was documented on a visual analogue scale (VAS). Each knee was also assessed for mobility and ligamentous stability.
Mean (SD) surgical time and type of approach was collected for each procedure, alongside the soft tissue releases performed and the need for femoral cut proximalisation. Stability, as well as dynamic patellar tracking, was assessed during the procedure by the surgeon (ET). Postoperative morphine consumption, blood transfusion and length of stay were also collected.
At the final assessment, the tibial and femoral components were assessed radiographically using the Knee Society roentgenographic evaluation system[31]. As well as for implant position, each component was assessed for the presence of radiolucent lines. Preoperative and final radiographic assessment included weight bearing full leg alignment to measure the mechanical alignment of the lower limb (HKA-angle)[19]. Outliers were defined as deviation of more than 3º from neutral alignment, as measured on a postoperative radiograph. Joint line restoration was measured in extension and in flexion[19]. In extension, the effect of the arthroplasty on patellar height, as measured with the modified Insall-Salvati ratio[32], was determined by comparing the preoperative and postoperative patella–patellar tendon ratio. This ratio was measured by determining the articular surface of the patella and the length of the patellar tendon to the insertion on the anterior surface of the proximal tibia.
Changes in preoperative and postoperative joint line position were documented. In flexion, the posterior condylar offset was evaluated on lateral radiographs by measuring the maximum thickness of the posterior condyle pre- and postoperatively, projected posteriorly to the tangent of the posterior cortex of the femoral shaft[15].
For the joint line and posterior condylar offset restoration, negative values indicated that the joint line position had been lowered, while positive values suggested that it had been raised.

Institutional Review Board approval was obtained by the Ethical Committee of the University Hospital Saint Luc, Brussels, Belgium.

Statistical Analysis
Sample characteristics are presented as numbers, means, SDs, and ranges. Categorical variables are presented as frequencies and percentages. The normal distribution of the data was assessed using the Kolmogorov-Smirnov test. The non-normally distributed data were analyzed using the nonparametric statistical Mann-Whitney test for independent samples and Wilcoxon signed rank test for dependent samples. Comparison of observed proportions was performed using Chi-square and Fisher's exact test. Logistic regression was used to assess the joint association of postoperative malalignment and the independent variables of interest: age; sex; and preoperative varus versus valgus angle. All analyses were performed using Stata 12.1 (StataCorp LP, College Station, TX, USA). A p-value of < 0.05 was considered significant.

Results

The mean (SD) preoperative varus deformity (N=30) was 165° (3°) (range, 169°–156°). Mean (SD) preoperative valgus deformity (N=16) was 196° (4.5°) (range, 191°–213°). Mean (SD) preoperative range of motion was 115° (15.6°).
The mean (SD) surgical time was 97 (18) minutes without a difference for varus or valgus knees. Postoperative morphine was administered following 44 surgeries, at a mean (SD) dose of 48 (29) mg. Two patients had mild postoperative mediolateral instability (<5 mm), of which one had anteroposterior instability. The mean (SD) postoperative drop in hemoglobin (Hb) was 2 (0.5) g/dl. One patient (2%) required postoperative blood transfusion. One patient experienced femoropatellar pain and postoperative patellar clunk. No other major postoperative complications were recorded. Mean (SD) length of stay was 5.5 (1.5) days.
Radiolucent lines were absent in 40 patients. Four patients had radiolucent lines under the medial and lateral tibial baseplate; two patients had lines more medially and 1 patient had lines more laterally. These four patients had small tibias (Vanguard PS size 63). Radiolucent lines were not observed around the femoral or patellar component. No aseptic loosening of components was seen.
By final follow-up, none of the patients required revision surgery and all implants were in situ. Mean (SD) overall postoperative mechanical alignment was 179.5º (3.0º) HKA-angle. The mean (SD) postoperative alignment for the varus group (N=30) was 178° (1°) with a range from 173° to 181°. The aim of the postoperative alignment was 178° from 2011 on based on the undercorrection literature [16]. Ten (30%) patients had a postoperative varus. The mean (SD) postoperative alignment for the valgus group (N=16) was 180° (3°) with a range of 178° to 187°. Three (19%) patients had a postoperative valgus deviation from neutral alignment >3º. Mean (SD) coronal plane alignment of the femur was 85.5º (1º), while that for the tibia was 90º (1º).
Postoperative clinical scores are presented in Table 1.

Table 1 Postoperative clinical outcomes

	Mean	**SD**
Range of motion [°]	126.0	10.0
Forgotten Joint Score	86.5	13.0
KOOS		
- Pain	92.5	8.5
- Other symptoms	93.0	6.5
- ADL	90.0	11.0
- Sport	39.5	25.0
- QOL	93.0	12.0
Knee Society Score		
- Knee Score	89.5	9.0
- Function Score	77.5	18.0

Abbreviations: KOOS: Knee Osteoarthritis Outcome Score; ADL: activities of daily living; QOL: Quality of daily life; SD: standard deviation.

The Knee Society score for pain (90 (10) and KOOS was significantly higher for the undercorrected patients (87/100) ($p<0.05$).
The mean (SD) change in joint line position in extension was -0.0 (0.5) mm. The mean (SD) change in posterior condylar offset was 2.1 (4.6) mm.
Logistic regression analysis revealed no significant associations between postoperative HKA angle deviation >3º and preoperative alignment, sex, age or the direction and magnitude of the preoperative deformity (Table 2).

Table 2 Logistic regression analysis of factors potentially associated with postoperative malalignment

	Odds ratio	**95% CI**
Preoperative varus alignment	2.1	0.5–9.7
Preoperative angle mechanical axis	1.0	0.9–1.2
Male gender	0.5	0.1–2.5
Age	1.0	0.9–1.0

Abbreviation: CI, confidence interval

Discussion

The most important finding of this study was that deformities over 10° of mechanical malalignment can be treated with primary implants if: the approach does not destabilize the soft tissue sleeve; releases are titrated with a needling technique; and the primary implant allows for full interchangeability of femoral and tibial sizes. Furthermore it was observed that PROM scores were higher for undercorrected varus alignment patients.
The management of osteoarthritis in the presence of severe valgus and varus deformities is a surgical challenge that has been considered as one that calls for the use of higher constraint (CCK) or even hinged prostheses[33]. Concerns have been raised in the literature about constrained designs due to their disappointing results[34], and higher rate of complications[35,36]. Constrained implants are associated with increased

polyethylene wear, higher modular and fixation interface stresses, reduced postoperative range of motion, increased operating time and prosthesis cost, and finally a high incidence of leg and thigh pain from canal invasion due to stem extension[33,34,37-42]. Constrained TKA is also associated with significantly more joint line elevation than unconstrained TKA in the valgus knee[43]. Varus–valgus constrained designs have been linked to removal of more femoral intercondylar bone to accommodate the femoral box[44] and an increased potential for aseptic loosening[45]. Despite recent work indicating that good outcomes can be obtained with constrained prostheses in primary cases[39], the recommendation that the minimum amount of constraint necessary to achieve stability should be used still holds[34,35].

In this series of patients presenting with substantial deformities, the implantation of a primary standard PS knee design provided sufficient stability, and appropriately restored functional outcome. Intraoperative switch to a more constrained design was unnecessary, which is partly attributable to the knee design that we used allowing full interchangeability of sizes, such that the femoral component size can be selected independently of the tibial size. In cases where a deep tibial cut is necessary because of important wear, the use of a constrained knee design, in combination with block augmentation, can be avoided by a low resection of the tibia and covering the bone with a small tibial component. Interchangeability of component sizes obviates the need for femoral component downsizing to match the femur to the small tibia. Downsizing of the femoral component would lead to flexion instability, and the use of a thicker polyethylene insert to prevent this. As a result, the joint line is elevated[46]. In a recent study comparing joint line elevation in patients with valgus deformity, revision for global instability was required in 6% of patients who received unconstrained TKA[43], where the mean joint elevation was 2.4 mm. Joint line elevation of +6 ± 2 mm, patella infera and impingement of the tibial post against the patellar component in deep flexion has been associated with constrained implants[46].

In the current series, a mean (SD) change in joint line position in extension of -0.0 (0.5) mm was achieved. This compares very favourably with results from previous investigations. One study of a posterior cruciate ligament–retaining, mobile-bearing TKA in 76 knees revealing a mean change in joint line position of +1.1± 4.6 mm[47], while a comparison of conventional and computer-assisted navigated (CAS) TKA in 493 primary TKAs suggested that conventional TKA was associated with an average joint line shift of 0.7± 4.4 mm and 0.6± 4.4 mm with CAS[48]. Furthermore, only two cases of postoperative instability were seen, suggesting that good ligament balancing was achieved.

Our findings show that the minimally invasive far medial subvastus approach, combined with an interchangeable PS implant, achieved excellent overall postoperative mechanical alignment, but a significant proportion of the cohort (28%) showing deviation from neutral alignment >3°. The majority of patients did not have any radiolucent lines on postoperative follow-up, and average clinical outcome scores were higher for the undercorrected varus knees than for the 180° HKA-aligned knees, suggesting the achievement of both good clinical outcomes and patient satisfaction. Furthermore, no patients required revision surgery. The observation of undercorrection in big deformities was made by other authors as well as the fact that undercorrected patients have better clinical outcome as observed for this study group[16]. It was also observed that the mean Forgotten Joint Score (FJS-12) of these patients was higher (86.5) than the score for a normal control (82) in the index study on the FJS-12 from Behrend et al.[16]. This finding suggest that relative realignment for severe deformities

results in a high degree of forgetting the joint because of the bad mechanical situation they were used to have previously.
During the literature review for this study it was observed that the scientific semantics about lower limb alignment are very confusing and that this makes it difficult to compare results among papers as recently found by other authors[16]. Mechanical and anatomical alignment measurements are used across each other and sometimes alignment compared to the vertical axis is used with a wide range of normality depending of the author[16]. In this paper a new classification in different degrees of severity is proposed (Table 3) based on a literature review and the clinical experience of this study.
One of the primary limitations of our study is its non-randomised, retrospective and observational nature, which leaves it open to selection bias. Furthermore, relying on data from a single centre means that the findings may not be applicable to other institutions, where other surgical and rehabilitation protocols may be employed. The relatively small number of patients also means that drawing firm conclusions over improvements is difficult. The strength lies in the fact that a single surgeon using the same surgical approach and the same primary implant (Vanguard PS, Biomet, Warsaw, IN, US) performed all the interventions.
Finally, after extensively reviewing the literature on mechanical alignment and lower limb deformities before TKA as well as our study group a new classification for terminology for deformities is proposed in Table 3.

Table 3 Classification of lower limb deformity and proposed terminology

Mechanical Deformity on HKA-axis	Terminology	
0° - 3°	Normally or well aligned	
4° - 10°	Common deformity	
11° - 20°	Substantial deformity	
21° - 30°	Important deformity	
> 30°	Extreme deformity	

Conclusion

Highly favourable clinical, radiographic and alignment outcomes can be achieved with TKA in patients with severe varus or valgus deformities without recourse to constrained implant designs. The combination of a minimally invasive far medial subvastus approach, interchangeable PS implants and soft tissue release with a piecrust needling technique may imply that the benefits of more conventional implant designs can be made available to patients who would not hitherto be considered as potential candidates. Despite accurate component positioning an important segment of patients retains their original alignment postoperatively on weight-bearing radiographs.

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Chapter V: Bone morphotypes of the varus and valgus knee

Based on the observation that substantial deformities are difficult to correct despite of correct component positioning[1] we tried to understand the origin of deformity and the causes of failure of correction. The observation that bowing and extra-articular deformity of the femur would be important features stimulated us to measure intra-articular joint angles.

Furthermore the observation of Bellemans et al. that part of the Caucasian population has a constitutional varus alignment[2] and the work of Victor et al. that showed that the joint line remained parallel to the floor[3] inspired us to an intra-articular deformity analysis based on full leg standing radiographs. The aim of this work was to determine if the group of valgus osteoarthritis (OA) patients would have a neutral axis before disease development and progression and would therefore present with some kind of constitutional valgus. Comparison for the valgus group with their pre-diseased knee would allow us to determine the constitutional alignment of the valgus knee as an analogy with the varus constitution.

This paper should allow us to define the target for accuracy during total knee arthroplasty (TKA). The overall aim has for decades been a neutral mechanical axis of 180° but if the varus population has a constitutional varus of 178°, the valgus population might have another value to aim for. The hypothesis leading to this study was that constitutional valgus exists as well as constitutional varus.

Bone morphotypes of varus and valgus knee

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Abstract

Background: Correction of coronal deformity with total knee arthroplasty (TKA) is an important feature in the treatment of osteoarthritis (OA). The hypothesis of this study was that bone morphology would be different in varus and valgus deformity both during OA as well as before arthritic disease.

Materials and Methods: Retrospective study with measurements on preoperative and postoperative full leg standing radiographs of 96 patients who underwent TKA. A single observer measured mechanical alignment, anatomical alignment, anatomical-mechanical femoral angle and intra-articular bone morphology parameters with an accuracy of 1°.

Results: Varus OA group has less distal femoral valgus (mLDFA 89°) than control group (87°) and valgus OA group (mLDFA 85°). Varus OA group has same varus obliquity as control group (MPTA 87°) but more than valgus OA group (MPTA 90°). Joint Line Congruency Angle (JLCA) is 3°open on lateral side in varus and control group and medially open in valgus OA group (2°).

Discussion: Varus deformity as measured with HKA-angle (HKA<177°) is a combination of distal femoral wear, tibial varus obliquity and lateral joint line opening. Valgus deformity (HKA>183°) is a combination of femoral distal joint line obliquity and wear combined with medial opening due to medial collateral ligament stretching. Constitutional valgus is observed before the development of OA with an HKA-angle of 184°. The clinical importance of bone morphotype analysis lies in showing the intra-articular potential of alignment correction when mechanical axis cuts are performed.

Conclusion: Bone morphology in varus and valgus deformity is different. The observed measurements explain deformity measured as HKA-angle. Constitutional valgus is on average 184° HKA. Perpendicular cuts to mechanical axes lead to lateral distal joint line overstuffing in the valgus knee and adequate soft tissue balancing is required.

Introduction

Restoration of neutral mechanical alignment has for decades been the goal in total knee arthroplasty (TKA)[4,5]. Patients presenting with osteoarthritis often have either varus or valgus deformity[6]. Depending of the degree of deformity, the surgical technique and the choice of implant with its proper amount of constraint, might differ[7].

Alignment of the lower limb can be described referencing of the vertical axis, the mechanical axis or the anatomic axis[5,8]. The vertical axis is a vertical line running distally from the centre of the pubic symphysis. The mechanical axis is determined by a line from the centre of the femoral head to the centre of the ankle joint and is composed by the femoral and tibial mechanical axis. The anatomic axis is based on the intramedullary canals of both femur and tibia and is usually about 5-7° of valgus compared to the mechanical axis[8-10].

Previous studies focused on overall mechanical alignment of the Caucasian population. Moreland et al. and Hsu et al. found an overall slight varus alignment in asymptomatic persons[5,10]. This was recently confirmed by Bellemans et al.[2]. Victor et al. confirmed that the joint line is parallel to the floor in constitutional varus patients[3]. Fahlman et al. found, based on radiographic evaluation, that 82% of the study participants had the same alignment for both knees, more often for varus deformities than for valgus or neutrally aligned knees[11].
Full leg standing radiographs have shown their importance in evaluating deformity and more in particular in valgus knees with stretching of the medial collateral ligament [12,13].
The importance of preoperative planning in TKA has been emphasized before. Deformity and bone morphology analysis can help the surgeon understand better the case he is going to perform and can help him decide the level of cuts to make and the amount of constraint to choose[14,15].
Neutral coronal alignment has been linked to implant survival[16-19], but in contemporary knee designs wear could became less crucial. Coronal alignment and individual positioning of the components has become more of an issue in the quest for better patient outcome with a returning interest in anatomical alignment like in the past[20] or in kinematic alignment as more recently[21,22].
The clinical importance of bone morphology analysis would lie in the information that surgeons would obtain from their preoperative deformity analysis during pre-TKA planning. It allows understanding where the deformity is and if an intra-articular correction is possible. It should also help with planning of ligamentous release and choice of constraint.
The aim of this study was to analyze bony anatomy in the coronal plane by measuring full leg weight bearing radiographs. It was this study's aim to compare the arthritic side with a non-arthritic side both for a varus and valgus alignment population. Different angles of the femoral and tibial coronal anatomy were compared both preoperatively and postoperatively after TKA. The hypothesis was that deformity in varus and valgus knees is different for diseased and pre-arthritic knees and that constitutional valgus alignment exists parallel to constitutional varus alignment.

Materials and methods

Within the consecutive patients operated between 2011 and 2015 by a single surgeon a group of patients were selected because they presented unilateral primary osteoarthritis (OA) and were planned for total knee arthroplasty (TKA) and had good quality full leg standing radiographs. These full leg radiographs were taken according to a standardized protocol both before and one-year after surgery. The contralateral side could not present more OA than Kellgren-Lawrence type II.
The study group consisted of 96 patients with a mean (SD) age of 70 (10) and a mean (SD) BMI of 30 (5). Fifty-one had a preoperative varus alignment defined as an HKA-angle of 177° or less and 45 had a preoperative valgus alignment defined as an HKA-angle of 183° or more.
One observer performed all measurements two times at different intervals of time with a measurement precision of 0.5° and the mean was utilized as study result. On the first ten patients, all measurements were measured three times and the intra-observer variability was determined as 1° for all measurements. All the measurements were performed on the PAC System (AGFA Healthcare, Belgium) of the hospital.

The following angles (in °) were measured on all standing full leg radiographs utilizing the angle measurements tool of the PAC System:

1. Hip Knee Ankle (HKA)-angle: measured as the angle from the centre of the hip to the centre of the knee to the centre of the ankle. A 0° angle between the femoral and tibial axis is expressed as 180° mechanical axis. Neutral mechanical alignment is considered 178° to 182°. A deviation into varus is measured as 177° or less and a valgus alignment as 183° or more.
2. Anatomical-Mechanical Axis (AMA) of femur: measured as the angle between the femoral mechanical axis and femoral anatomical axis.
3. Femoral Neck Angle: angle between the proximal anatomical femoral axis and the femoral neck to centre of femoral head.
4. Mechanical Lateral Distal Femoral Angle (mLDFA): angle between the tangential of the distal femur and the mechanical axis of the femur.
5. Mechanical Proximal Tibial Angle (MPTA): angle between the tangential of the proximal tibia and the mechanical axis of the tibia.
6. Joint Line Congruency Angle (JLCA): angle between the tangential of the distal femur and the tangential of the proximal tibia.
7. Anatomical Lower Limb Alignment: angle between the anatomical axes of femur and tibia.

Statistical analysis

Statistical analyses were performed using the Statistical Package for Social Science software (SPSS), version 21.0, for Windows (SPSS Inc., Chicago, IL, USA). Sample characteristics are presented as numbers, means and standard deviations. Categorical variables are presented as frequencies and percentages. The normal distribution of the data was assessed using the Kolmogorov–Smirnov test. The non-normally distributed data were analysed using the nonparametric statistical Mann–Whitney test for independent samples and Wilcoxon signed-rank test for dependent samples. Comparison of observed proportions was performed using Chi-square and Fisher's exact test. A p value of < 0.05 was considered significant.

Results

Measurements for preoperative and postoperative lower limb alignment for the total study group are given in Table 1.

Table 1 Measurements of the operated limb for general study group

N = 96	Preoperative				Postoperative				p-value
	Mean	SD	Min	Max	Mean	SD	Min	Max	
HKA-angle (°)	**180**	**8**	162	197	**180**	**3**	172	184	Ns
AMA-angle (°)	**7**	**1**	4	10	**7**	**1**	4	10	Ns
Femoral neck angle (°)	**127**	**7**	109	142	**126**	**13**	110	141	Ns
mLDFA (°)	**87**	**3**	78	99	**90**	**2**	81	97	0.0001
MPTA (°)	**87**	**3**	78	94	**90**	**2**	88	93	0.0001
JLCA (°)	**3**	**3**	0	11	**0**	**1**	0	3	0.0001
FA-TA-angle (°)	**187**	**7**	168	204	**187**	**3**	171	193	Ns

Measurements for varus group on operated side are given in Table 2.

Table 2 Measurements of the operated limb for the varus group

N = 51	Preoperative				Postoperative				p-value
	Mean	SD	Min	Max	Mean	SD	Min	Max	
HKA-angle (°)	**173**	**5**	162	177	**180**	**3**	172	181	0.0001
AMA-angle (°)	**7**	**1**	5	9	**7**	**1**	5	10	Ns
Femoral neck angle (°)	**126**	**7**	109	139	**126**	**6**	110	136	Ns
mLDFA (°)	**89**	**3**	85	99	**90**	**3**	81	97	0.0011
MPTA (°)	**87**	**3**	78	91	**90**	**2**	88	93	0.0001
JLCA (°)	**3**	**2**	0	11	**0**	**1**	0	2	0.0001
FA-TA-angle (°)	**182**	**4**	168	190	**186**	**3**	179	193	0.0001

Measurements for valgus group on operated side are given in Table 3.

Table 3 Measurements of the operated limb for the valgus group

N = 45	Preoperative				Postoperative				p-value
	Mean	SD	Min	Max	Mean	SD	Min	Max	
HKA-angle (°)	**187**	**4**	181	197	**180**	**3**	178	184	0.0001
AMA-angle (°)	**7**	**1**	4	9	**7**	**1**	4	9	Ns
Femoral neck angle (°)	**129**	**7**	116	142	**126**	**20**	115	141	Ns
mLDFA (°)	**85**	**3**	78	89	**90**	**2**	86	94	0.0001
MPTA (°)	**90**	**3**	84	94	**90**	**3**	89	92	0.0038
JLCA (°)	**2**	**3**	0	9	**1**	**1**	0	3	0.0001
FA-TA-angle (°)	**193**	**5**	185	204	**186**	**3**	171	192	0.0001

Results for the non-operated side for general group are given in Table 4, for the non-operated varus group on the left side of Table 4 and for non-operated valgus group on the right side of Table 4.

Table 4 Measurements of the non-operated limb

N=96	Varus (N=51)				Valgus (N=45)				p-value
	Mean	SD	Min	Max	Mean	SD	Min	Max	
HKA-angle (°)	**178**	**3**	166	177	**184**	**3**	183	190	Ns
AMA-angle (°)	**7**	**1**	3	11	**7**	**1**	5	10	Ns
Femoral neck angle (°)	**126**	**7**	105	137	**127**	**6**	117	141	Ns
mLDFA (°)	**87**	**2**	78	93	**86**	**3**	83	96	Ns
MPTA (°)	**87**	**3**	80	98	**90**	**3**	86	98	0.0403
JLCA (°)	**3**	**2**	0	8	**1**	**1**	0	5	0.0001
FA-TA-angle (°)	**183**	**3**	174	187	**189**	**3**	183	198	0.0001

Discussion

The most important finding of this study was that varus deformity finds it origin in medial tibial disease and lateral joint distraction. If varus deformity is more substantial, the deformity is sometimes intra-articular on the femoral side but usually extra-articular.

In valgus deformity the deformity is mostly extra-articular on the tibia but with a 90° tibial joint line and a substantial distal femoral valgus anatomy. Correction of valgus deformity needs to be performed on the femoral side principally.

Bone morphotype analysis allows knowing how much deformity correction can be obtained by the valgus correction angle.

Demuylder et al. classified deformities according to the degree of deformity into well-aligned knees (0-3° deviation), common deformities (4-10°), substantial deformities (11-20°), important deformities (21-30°) and finally extreme deformities (>30°).

They observed, as well as other authors, that important and extreme deformities are much more difficult to correct to neutral mechanical alignment if performed with conventional instrumentation[1]. This study showed that deformities over 10° usually have an extra-articular component. For the varus knee this is usually femoral bowing[23] and for the valgus knee intrinsic valgus deformity can be observed both on the tibial and femoral side[24].

The current study showed that a horizontal bony joint line is obtained for the total study population by a neutralization of the medial tibial joint line obliquity of 3° (MPTA-angle 87°) by an inversed distal femoral joint line obliquity (mLDFA-angle of 87°). The mean varus alignment of the lower limb (178° HKA°) observed in other studies[2,5,10] and in our control group (Table 4) is probably a result of lateral soft tissue laxity with joint line opening (JLCA of 3°) on the lateral side in varus knees. In the varus OA group (mean (SD) 173° (5°)) the mLDFA was 89° and the MPTA 87° combined with a JLCA of 3°. This finding suggests that not so much intra-articular deformity correction can be obtained on the femoral side but mostly on the tibial side and on the soft tissue release in extension on the concave side (medial collateral ligament in extension). In the valgus OA group (mean (SD) 187° (4°)) the mLDFA was 85°and the MPTA 90° combined with a JLCA of 2°. This finding suggests that most of the valgus correction should be performed on the femur by a varisation, cut of about 5° AMA and adequate soft tissue release of the iliotibial band (ITB) in extension.

The current study also found that the angle between the anatomical femoral axis and the mechanical femoral axis is a mean (SD) of 7 (1) for both varus and valgus OA patients[4,20,25] but with an important variance as observed by other authors[26]. In the varus group this distal femoral cut reduces the intrinsic valgus of the femur very slightly from mLDFA 89° to 90°, but in the valgus group the mLDFA of 85° becomes 90°. This means that the lateral distal joint line is distalized. Furthermore is the JLCA in the varus group laterally open for 3° and in the valgus group it is closed for 2° due to medial collateral ligament stretch. Both findings suggest potential overstuffing of the lateral compartment asking for sufficient soft tissue release on the ITB in extension. This was also observed by other authors[27,28].

Another finding of this study was that the femoral neck angle was more in valgus with valgus OA deformity of the lower limb. After surgery this angle returned to the mean valgus angle observed for patients without OA (Table 4) and to the mean for the varus OA group. This observation must be due to a change of position of the operated leg[29]. In valgus deformity the foot must be more outside to compensate for the load-bearing axis running lateral from the knee joint[17]. Furthermore in valgus OA often external rotation is observed, which will be corrected after surgery[30]. This correction of rotation could have lead to another femoral neck angle measurement on the full leg standing radiographs[12,31].

A final finding of this study was that constitutional valgus existed in this valgus group. An HKA-angle of 184° was observed for patients with valgus alignment that had not developed OA yet. This is probably a similar finding as to what Bellemans et al. found for constitutional varus[2].

A first weakness of this study is that one observer performed all measurements and therefore this study has no inter-observer variability of measurements. The intra-observer variance was well studied and the experience of the observer lead to an intra-observer variability of 1° on all measurements what is within the range of the accuracy of the PAC System. Bowman et al. found intra-class correlation (ICC) of >0.9 for measurements of mechanical alignment on long leg radiographs[32].

A second weakness is that all measurements were performed on full leg radiographs and not with CT allowing a correction for rotational mistakes[30]. The ethical committee of our institution would not have accepted however performing CT on all the study persons for this study. Full leg radiographs are standard of care before and after total knee arthroplasty at our institution. The advantage of these radiographs is that they are performed under standard conditions and that they are load bearing giving information about the dynamics of deformity with the impact of soft tissue laxity on the convex side[12,29].

A final weakness is that all patients for this study were randomly selected on the basis of the presence of a good quality preoperative and one-year postoperative full leg radiograph. Therefore patients with substantial and important deformities were included. A previous study showed that correction to neutral mechanical alignment cannot be obtained with conventional instruments in those cases [1]. The observations of these measurements show that bowing or extra-articular deformities cannot be corrected by cuts perpendicular on the mechanical axes, except if an adapted entry hole is utilized [23]. Despite of adequate correction of the intra-articular deformity, important outliers in HKA were still observed (Table 2 & 3).

The strength of this study lies in the measurements performed on two groups of patients with good quality full leg radiographs all measured by a single observer with experience in radiographic measurements with an accuracy within 1° giving interesting data about bone morphology in varus and valgus deformities, both in OA and before arthritis helping us better understand the angles of deformity.

The clinical importance of these study findings lies in the understanding that accurate preoperative planning before TKA can help the surgeon obtain accuracy in postoperative coronal alignment. If the measured deformity is more important than the measured intra-articular angles, an extra-articular deformity should be suspected. Bone morphotype analysis allows estimating the deformity correction that will be obtained by distal valgus AMA correction. This study confirms furthermore the need of full leg radiographs in preoperative planning for TKA. Finally, this study shows how important joint line changes in the valgus knee, with distalisation on the lateral side, will ask for fine-tuning of the lateral soft tissues to obtain good clinical outcome. In the non-arthritic knees constitutional valgus with a mean 184° HKA was observed.

Conclusion

Varus deformity, in an OA and varus aligned population, originates from tibial varus joint line obliquity and wear at the medial distal condyle in more important deformity. Lateral compartment laxity increases varus alignment measurements. Valgus deformity in an OA and valgus aligned population, originates from distal femoral valgus joint line obliquity and medial laxity due to medial collateral ligament stretching.

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Chapter VI: A new classification for the varus knee

Introduction

Joint replacement will only be successful if accuracy is achieved for each of the three knee planes. There has been extensive research into the optimal alignment of the axial plane in relation to both patellar tracking and gap stability. Coronal alignment, which has been linked to early failure and polyethylene wear, also needs to be considered when describing the deformity preoperatively, as well as analyzing the radiological outcome[1].

Varus alignment is present in the majority of osteoarthritic knees[2,3]. This is potentially because intrinsic varus alignment is more common within the general population[4]. Varus alignment has also been linked with obesity. A majority of total knee arthroplasties (TKAs) are performed in cases where varus deformity is present. Despite its preponderance, there is, to the best of our knowledge, no classification system for varus deformity prior to knee arthroplasty.

There are, however, two methods for classifying the radiological severity of knee arthritis: the Kellgren-Lawrence and the Ahlback rating of radiographs. Although the majority of TKA-eligible patients will be in the III-IV group for either of these classifications, this information is of little use for surgeons in terms of indicating different types of implants and predicting technical difficulties during the procedure[5,6].

Therefore, the aim of this retrospective study, which comprises a wide variety of cases, is to propose a classification system for knees suffering from medial compartment arthritis so that surgeons can gain a greater insight into varus pathology of the knee.

A new classification for the varus knee

Adapted from: Thienpont E, Parvizi J. A new classification for the varus knee. J Arthroplasty 2016.
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Abstract

Background A new classification for osteoarthritis of the knee associated with varus deformity is presented. This classification is derived from the combination of conventional radiographs, stress radiographs (when needed) and clinical examination.
Methods: This study included the analysis of coronal alignment on full leg standing radiographs of 526 patients awaiting knee arthroplasty for varus deformity in a single institution. Various mechanical and anatomical angles were measured and these findings were combined with a basic clinical examination of patients. The radiographs were measured on two separate occasions to determine the intra-observer reliability. Cross sectional studies such as CT or MRI, were utilized to further refine observations about different wear patterns.
Results: Varus deformity can either be intra-articular or extra-articular. Intra-articular deformities can be correctable or fixed. In fixed deformities the status of the lateral ligament is taken into account. Extra-articular deformity can be metaphyseal or diaphyseal and the possibility for intra-articular correction will depend on the degree of deformity and its distance from the joint.
Conclusion: This new classification allows for better definition of varus deformity, which can help surgeons during preoperative planning, particularly with their choice of implant and potentially the degree of constraint. The classification can also be a tool for further prospective studies about varus deformity.

Introduction

Coronal alignment is an important factor in orthopaedic surgery, both preoperatively to describe the deformity as postoperatively to observe and report the radiological outcome[1]. Coronal alignment can be evaluated as an anatomical femorotibial angle, which is usually 6° of valgus relative to a vertical reference through the pubic symphysis. The anatomical axes for this measurement are determined as lines drawn through the centre of the femoral and tibial intramedullary canals[7]. The anatomical axis can be found both during surgery as on radiographs. This allows the surgeon to align the limb according to the mechanical axis while using the anatomical axis available during surgery. The difference measured between the mechanical axis and the anatomical axis of the femur is referred to as the femoral mechanical-anatomical angle (FMAA), which is perhaps the most critical aspect of alignment. The FMAA angle changes with height and pelvic width[8].
Coronal alignment can also be evaluated as mechanical alignment, which can be measured on a full leg standing radiograph[9,10]. First, a line running from the centre of the femoral head to the centre of the talus, the load bearing axis line or Maquet's line, can be used[11]. Neutral mechanical alignment runs from the centre of the hip through the centre of the knee and through the centre of the talus. If there is varus deformity, the Maquet line will cross the tibia more medially or even medial to the knee joint in cases of severe varus deformity.

Mechanical alignment can also be measured as a coronal plane angle. Therefore, the angle between a line from the centre of the hip (H) to the centre of the knee (K) and a line from the centre of the knee (K) to the centre of the ankle (A) will be drawn on full leg radiographs. The angle where both lines cross each other at the knee joint is the hip knee ankle (HKA) angle. The HKA angle is expressed in the coronal plane in terms of 180° if both lines run parallel. In cases of varus deformity, by definition, the angle is less than 180° and in case of valgus deformity it is greater than 180°[10]. Neutral alignment in the coronal plane is considered alignment within 3° of the 180° HKA angle[4,9,10,12] and therefore knees with varus alignment should measure 177° HKA or less[13].
The majority of osteoarthritic knees present with varus alignment[2,14]. This may be explained by the tendency of intrinsic varus alignment of the general population[4,12]. Obesity also plays a crucial role in the development of varus alignment. Consequently, about 90% of total knee arthroplasties (TKAs) are implanted due to varus deformity[2,14]. Despite of the high frequency of varus pathology, to the best of our knowledge, no classification for varus deformity prior to knee arthroplasty exists.
However, two popular radiological classifications exist to classify severity of arthritic knees, which are the Ahlback and the Kellgren-Lawrence rating of radiographs. Most patients eligible for TKA will be in the Ahlback III-IV or Kellgren-Lawrence III-IV group, but this does not really help surgeons foresee potential technical difficulties of the scheduled surgery[5,6].
Recently, a new classification for the severity of arthritic disease was proposed utilizing simple semantic terms that will allow surgeons to compare deformities in the near future. Mechanical alignment within 3° was considered normal and a deformity within 4° to 10° a common deformity. With increments of 10°, the classification considers 11° to 20° a substantial deformity, 21° to 30° an important deformity, and greater than 30° an extreme deformity[3].
The purpose of this retrospective study on a wide variety of surgical cases is to propose a new classification for the different types of varus knees suffering from medial compartment arthritis. This classification tries to help surgeons better understand and structure varus pathology of the knee.

Materials and methods

Preoperative full leg radiographs of 526 patients who underwent TKA for varus deformity between 2012 and 2015 in a university hospital with a single surgeon, were retrospectively analyzed. Only patients who underwent a full leg standing radiograph preoperatively were included. Both primary osteoarthritis and posttraumatic arthritis were eligible for the study. Patients with rheumatoid arthritis were excluded as the inflammatory nature of the disease was believed to affect the periarticular tissues including the collateral ligaments without any association with the deformity. All patients were Caucasian with 212 (40%) males and 314 (60%) females. The mean ± standard deviation (SD)_age of the patients in the entire cohort was 67 ± 10 years without a significant difference between men and women. The mean body mass index was 30.5 ± 5.5 kg/m^2. The mean preoperative HKA alignment was 173° ±5° (range, 149°-177°). Thirty-six percent of the study group patients underwent unicompartmental arthroplasty (UKA) and 64% received TKA. The degree of arthritis in the knees was classified using the Kellgren-Lawrence and Ahlback knee arthritis classification (Table 1). Hundred ninety-five patients had received MRI and 331 patients had CT-

Arthrography of their knee preoperatively. The results of these cross sectional studies were incorporated into the study whenever possible.

Table 1 Kellgren-Lawrence classification of medial femorotibial arthritis

Kellgren-Lawrence grading	% of study group (N)	Ahlback grading	% of study group (N)
1	0.5 (2)	1	0.5 (2)
2	7 (37)	2	2.5 (13)
3	22.5 (118)	3	27 (142)
4	70 (369)	4	70 (369)

One observer who measured the full leg radiographs twice for each patient performed all measurements. The intra-observer accuracy was 1° as measured by 10 consecutive measurements at the start of the study. The intra-observer reliability of the classification was measured by comparing the second evaluation with the first observation. The Cronbach method was used to determine the score that is a measure of intra-observer reliability. A Cronbach score of 0.90 was obtained.

Proposed Classification

Intra-Articular deformity (Type IA)

1. Reducible anteromedial osteoarthritis (AMOA) with an intact anterior cruciate ligament (ACL): typically Kellgren-Lawrence grade IV femorotibial disease with bone-on-bone contact. Anteromedial location can be observed on advanced imaging such as magnetic resonance imaging (MRI) or computed tomography (CT) arthrography.
2. Reducible posteromedial osteoarthritis (PMOA) with a deficient ACL: Kellgren-Lawrence grade IV femorotibial disease with bone-on-bone contact. Posteromedial wear can be observed on radiographs and confirmed by MRI or CT arthrography.
3. Fixed varus deformity without lateral laxity.
4. Fixed varus with lateral laxity.

Metaphyseal deformity (Type M) (within 5 cm of joint line) either at the femoral (F) or tibial (T) level

1. Metaphyseal involvement because of wear (bone defects).
2. Metaphyseal involvement because of changed joint line obliquity.

Diaphyseal deformity (Type D) (at least 5 cm away from joint line)

1. Deformity at the tibial level (DT).
2. Deformity at the femoral level (DF).
3. Deformity at the tibial and femoral level combined (DTF).

Type IA stands for Intra-Articular wear. Type IA can be grossly classified according to the reducibility of the varus. The reducible varus can be either anteromedial or posteromedial. AMOA is clearly seen on lateral radiographs, which shows that the ACL is intact. If PMOA is present, this is suggestive for a tear of the ACL. Fixed varus can exist with or without lateral laxity. The former is often present in cases with varus thrust and usually seen after a previous ACL tear and extra-articular reconstruction of the knee.
The second type of varus osteoarthritis, Type M, is a metaphyseal deformity extending from the epiphyseal region but within 5 cm of the joint line. This type of varus knee has so much medial wear because of collapse or avascular necrosis of the plateau that the disease extends beyond the epiphyseal area of the proximal tibia. Usually the disease remains within the metaphyseal area. Within the metaphyseal area, changes to the joint line obliquity can also be observed either by congenital disease such as Blount's disease or by idiopathic changes with rarely a reversed joint line obliquity. However, metaphyseal changes are most frequently the result of surgical interventions like high tibial osteotomy (HTO), corrective distal femoral osteotomy (DFO) or treatment of peri-articular fractures.
The third type of varus deformity is a diaphyseal deformity or Type D that should be at a distance greater than 5 cm from the joint line. This extra-articular deformity can be either at the distal tibia (DT) level, distal femoral (DF) level, or combined at the distal tibial and femoral level (DTF) level.

Results

Table 2 presents the results of the study group according to the newly proposed varus classification. Table 3 shows the frequency of diaphyseal deformity according to anatomical location.

Table 2 Frequency of different types of varus arthritis in study group (N=526)

Type I (Intra-articular)	N	%
AMOA with intact ACL	422	80
PMOA with deficient ACL	63	12
Type M (Metaphyseal)	15	3
Type D (Diaphyseal)	26	5

AMOA: anteromedial osteoarthritis; ACL: anterior cruciate ligament; PMOA: posteromedial osteoarthritis.

Table 3 Classification of anatomical location in diaphyseal deformity group

Type	N	Percentage
DT	15	3
DF	9	2
DTF	2	0.5

DT: diaphyseal tibia; DF: diaphyseal femur; DTF: diaphyseal tibia and femur combined.

Discussion

After analyzing full leg radiographs of a consecutive series of patients awaiting TKA, a new classification for knee osteoarthritis with varus deformity is proposed. The classification intends to help surgeons better prepare for TKA by selection of the appropriate implant and eventually the correct degree of constraint. The classification makes a distinction between intra-articular and extra-articular deformities as well as the flexibility of the deformity.

Type IA wear patterns were stratified according to basic clinical and radiological features. AMOA with intact ACL is usually limited to the anteromedial part of the tibia and femur and can be considered an indication for UKA[15,16]. If the ACL is no longer intact, clinical laxity can be observed and in general posteromedial arthritis is observed[17-19]. This can be seen on standard lateral radiographs and should be considered an indication for TKA. Previous papers about the absence of the ACL in knee arthritis observed this in 14.5% to 17% of cases, comparable to our findings in this study (12%)[20]. Fixed varus deformities that are in need of medial releases are usually an indication for TKA since one of the principles of successful UKA is the avoidance of ligament release[15]. Patients who have a gait pattern with an important varus thrust[21] can develop lateral laxity and should be well aligned, if not in a little valgus, to reduce this lateral collateral ligament laxity. The use of more constrained implants could also be a solution in cases with remaining collateral laxity[22].

Type M deformities are varus deformities that are either femoral (Type MF) or tibial (Type MT). Important tibial or femoral wear with bone loss can be observed after progression of the disease, usually in important or extreme deformities[3]. Depending on the level of the wear, a choice between bone grafting and metal substitution should be made[23-25]. Metaphyseal deformity without bone loss is usually either posttraumatic, due to metabolic bone disease (Paget, Rickets, …) or congenital conditions (tibia vara, Blount, …). It can also be iatrogenic after previous osteotomies about the knee[26]. Depending on the amount of deformity a choice should be made between corrective osteotomy or intra-articular correction combined with a more constrained implant.

Finally, diaphyseal deformities up to the metaphysis of the hip or ankle (Type D) can be classified depending on the anatomical localization: DT, DF, or DTF. Depending on the level of the deformity the correction can be performed with an intra-articular osteotomy for the implant or should be corrected extra-articularly with a corrective osteotomy[27-29]. The impact of the deformity on the mechanical alignment and the option to correct it with an intra-articular osteotomy should be studied preoperatively. The varus effect of the extra-articular deformity can be calculated at its apex and then multiplied by the distance to the joint line. A deformity at the midlevel of the femur (50%) has a 0.5 impact on the varus alignment of the leg. If that angle is smaller than the osteotomy

needed through the lateral distal condyle without breaching the insertion of the collateral ligament, an intra-articular correction can be performed. However, the impact on soft tissue laxity in extension should be evaluated first.
Knee osteoarthritis with varus deformity is the most common form of bone-on-bone arthritis. This proposed varus classification (Table 4) is a simple way of organizing varus pathology, similar to the Krackow valgus classification[30], to make prospective studies and treatment options available to surgeons performing TKA.

Varus deformity classification according to "Thienpont and Parvizi"

Type IA: Intra-articular deformity
Reducible
    AMOA with ACL intact (Figure 1)
    PMOA with deficient ACL (Figure 2)
Fixed
    Without lateral laxity
    With lateral laxity

Type M: Metaphyseal (within 5 cm of joint line) at femoral (F) or tibial (T) level
Wear extending to the metaphyseal region
Changes to joint line obliquity and metaphyseal anatomy

Type D: Diaphyseal (greater than 5 cm away from joint line)
DT: Deformity Tibial level
DF: Deformity Femoral level
DTF: Deformity Tibial and Femoral level

AMOA, anteromedial osteoarthritis; ACL, anterior cruciate ligament; PMOA, post-eromedial osteoarthritis

Figure 1 *shows Type IA with anteromedial osteoarthritis.*

Figure 2 *shows Type IA with posteromedial osteoarthritis.*

Figure 3 *shows Type IA with fixed medial osteoarthritis without lateral laxity.*

Figure 4 *shows Type M with metaphyseal involvement because of important tibial wear.*

Figure 5 *shows Type M with metaphyseal involvement because of reversed joint line obliquity after previous high tibial osteotomy.*

Figure 6 *shows Type D with diaphyseal involvement at the femoral level.*

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Chapter VII: Accuracy, precision and trueness of alignment after total knee arthroplasty with conventional instruments

Introduction

Accuracy is defined as the closeness of a measured value to the actual true value (an accepted reference value). It determines the capacity to reach the target value. It is a measurement with both true and consistent results. An accurate measurement has no systematic error and no random error. Accuracy comes as the combination of trueness and precision.

Trueness is defined as the closeness of an average measurement (arithmetic mean) to a true value, while accuracy is the closeness of a single measurement to the true value. Trueness is the estimate of the systematic error.

Precision is defined as the closeness of two or more measurements to each other, so it measures the ability to consistently reproduce the same value. Precision is associated to the standard deviation as it's quantitative expression. It is the estimate of the random error, which usually comes from unknown and unpredictable changes. Two important conditions of precision are repeatability and reproducibility describing the minimum and the maximum variability in results.

Error is defined as the difference between the measured value and the true value. This error can either be a systematic error or a random error. A systematic error, is a component of error that varies in a predictable way. A random error, is a component of error that varies in an unpredictable way. The maximum error should be of our interest in alignment analysis.

Bias is estimated as the difference of the mean value of several measurements from the reference value. Bias is the total systematic error.

The reason for the current study was the concept that the analysis of a heterogeneous group of osteoarthritis patients would give us an idea about the true value of neutral alignment. Furthermore an analysis of trueness would give us an estimate of the systematic error of conventional instrumentation. The analysis of precision would give us an estimate about the random error that occurs like malpositioning of a cutting block or anatomic variations of the femoral or tibial anatomy. It measures the repeatability of the procedure and how close to each other two measurements are.

Accuracy, precision and trueness of alignment after total knee arthroplasty with conventional instruments

Emmanuel Thienpont, Pierre-Emmanuel Schwab, Olivier Cornu, Johan Bellemans, Jan Victor.

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Abstract

Mechanically aligned total knee arthroplasty is the golden standard for several decades now. Initially, this alignment was considered important for implant survivorship. Today, it is seen as a potential cause of dissatisfaction for patients.

The aim of this study was to determine the trueness of 180° hip-knee-ankle (HKA) angle as the target for total knee arthroplasty. Furthermore precision, bias and accuracy of conventional instruments are determined in a mixed alignment study population.

The trueness of preoperative HKA was 178.5° with a predominant varus population. The postoperative HKA was 179.5° with a 95% CI of 179.0°-180.0°.

The bias for the medial proximal tibial angle was 1.0° and the precision 2.5°. For the lateral distal femoral angle the bias was 2.0° with a precision of 5.0°. The joint line congruency angle showed a bias of 0.5° and a precision of 1.5°.

Overall component accuracy is influenced by the femoral position in the coronal plane with especially variations of the distal valgus angle cut, bowing or extra-articular deformities being responsible for a reduction of surgical precision.

Introduction

Alignment in the frontal or coronal plane is important both for the preoperative evaluation of the osteoarthritic knee as for the postoperative outcome study of total knee arthroplasty (TKA)[1]. Frontal plane alignment variations have also been related to the pathogenesis of knee osteoarthritis (OA)[2]. For the analysis of frontal alignment the orientation of the femur and tibia can be described in terms of the bones' mechanical or anatomical axes[3]. The orientation of these axes describes static alignment, which can be neutral, varus (bowlegged) or valgus (knock-kneed)[2]. Using mechanical axes, alignment can be described as the Hip-Knee-Ankle (HKA) angle that can either be neutral (180° ± 2°), lower than 178° and represent varus alignment or higher than 182° and represent valgus alignment[3,4]. Deformity can also be described as a medial displacement from the load-bearing axis (LBA) running from the centre of the hip to the centre of the ankle. A lateral displacement of the centre of the knee compared to the LBA is varus alignment and a medial displacement of the centre compared to the LBA is valgus alignment[2].

Neutral frontal mechanical alignment with 180° HKA as the absolute true value or target for coronal TKA alignment has become more controversial recently since wear of polyethylene components is probably less of an issue. Parratte et al. observed that patients who presented with outlier alignment not necessarily had more revisions than the neutrally aligned group[5]. Several other authors confirmed this finding also[6,7]. Furthermore, Vanlommel et al. observed that undercorrected TKA in preoperatively varus aligned knees did functionally better[8]. This can easily be understood if a varus aligned population has a coronal alignment of 178° and not of 180°[4,9,10]. Finally, kinematically aligned knees where the deformity was not restored to neutral alignment but to a pre-arthritic state showed superior outcome[11,12].

Several devices to improve accuracy are available today. These vary from computer navigation (CAOS) to accelerometer-based devices, patient specific instruments (PSI) and robotics[13-16]. With all the controversy about alignment and the true value for alignment, accuracy improving devices could loose their value or become more important than ever if the question remains what the exact target should be[17].
The hypothesis of this retrospective study was that the true value of neutral alignment as well as for varus or valgus alignment could be obtained from a study group of OA patients awaiting TKA. After determining the target for alignment, precision and trueness will be studied for TKA patients operated with conventional instruments.

Materials and methods

Within the consecutive patients operated between 2013 and 2015 by a single surgeon a group of patients were selected because they presented primary osteoarthritis (OA) and had undergone total knee arthroplasty (TKA) with conventional instrumentation. Good quality full leg standing radiographs, both preoperatively and postoperatively, were on file as well as short film radiographs. The full leg radiographs were taken according to a standardized protocol both before and one-year after surgery. All patients had the same type of TKA implanted (Vanguard PS, Zimmer Biomet, Warsaw, IN, US). The distal femoral valgus angle was set at a fixed value of 5° because we intended to undercorrect the varus knees and correct the valgus knees to neutral alignment, if possible. Extra-medullary alignment was used on the tibial side. Flexion gap stability was obtained with a spacer technique and soft tissue releases were performed with a piecrust technique until symmetrical laxity of 2 mm was obtained[18].
The study group consisted of 83 patients with a mean (SD) age of 69 (10) and a mean (SD) BMI of 30 (5). Fifty-two (63%) had a preoperative varus alignment defined as an HKA-angle of 177° or less and 27 (32%) had a preoperative valgus alignment defined as an HKA-angle of 183° or more. Four (5%) patients had neutral mechanical alignment of 178° to 182°.
One observer performed all measurements two times with a measurement precision of 0.5° at different intervals of time. The mean of both measurements was utilized as the definitive value for study analysis. On the first ten patients all measurements were measured three times and the intra-observer variability was determined as 1° for all measurements. All the measurements were performed on the PAC System (AGFA Healthcare, Belgium) of the hospital.

The following angles (in °) were measured on all standing full leg radiographs utilizing the angle measurements tool of the PAC System:

1. Hip Knee Ankle (HKA)-angle: measured as the angle from the centre of the hip to the centre of the knee to the centre of the ankle. A 0° angle between the femoral and tibial axis is expressed as 180° mechanical axis. Neutral mechanical alignment is considered 178° to 182°. A deviation into varus is measured as 177° or less and a valgus alignment as 183° or more.
2. Mechanical Lateral Distal Femoral Angle (mLDFA): angle between the tangential of the distal femur and the mechanical axis of the femur.
3. Medial Proximal Tibial Angle (MPTA): angle between the tangential of the proximal tibia and the mechanical axis of the tibia.

4. Joint Line Congruency Angle (JLCA): angle between the tangential of the distal femur and the tangential of the proximal tibia.

Accuracy was defined as closeness of the measured value to the actual true value (178° HKA for varus group and 180° HKA for the others). It determines the capacity to reach the target value. It is a measurement with both true and consistent results. An accurate measurement has no systematic error and no random error.
Precision was defined as the closeness of two or more measurements to each other, so it measures the ability to consistently reproduce the same value. Precision is associated to the standard deviation (SD) as its quantitative expression and is a description of random errors or a measure of statistical variability. It is the estimate of the random error, which usually comes from unknown and unpredictable changes.
Trueness is defined as the closeness of an average measurement to a true value, while accuracy is the closeness of a single measurement to the true value. It is the estimate of the systematic error.
Error is defined as the difference between the measured value and the true value. This error can either be a random error or a systematic error.
Bias is defined as the difference between the mean of all test results and the reference value.

Statistical analysis
The unsigned and signed differences between the postoperatively measured alignment and neutral alignment were calculated for HKA, MPTA, LDFA, and JLCA. Signed differences represent systematic deviation from the intended alignment, e.g as a tendency of resection towards varus or towards valgus. Unsigned differences, in contrast, represent precision (random error). Precision was estimated by adding the mean error and two times the SD of the mean error, as about 95% of the observations will fall within two standard deviations of the mean. For HKA, accuracy precision and trueness together were summarized in folded cumulative distribution curves (mountain plots)[19,20]. We constructed separate plots for preoperative varus and valgus morphology.

Results

Table 1 shows the results for preoperative HKA-angle for overall study population and for the three alignment groups.

Table 1 Preoperative HKA-angle

Alignment	N	Mean	SD	Range	95% CI
Total study group	83	178.5°	7.5°	162.0°-197.0°	177.0°-180.0°
Neutral group	4	180.0°	2.0°	178.0°-182.0°	178.0°-182.0°
Varus group	52	174.0°	4.5°	162.0°-177.0°	173.0°-175.0°
Valgus group	27	187.0°	4.0°	183.0°-197.0°	185.5°-188.5°

Table 2 shows the results for postoperative HKA and for the three alignment groups.

Table 2 Postoperative HKA-angle

Alignment	N	Mean	SD	Range	95% CI
Total study group	83	179.5°	3.0°	172.0°-186.0°	179.0°-180.0°
Neutral group	4	181.0°	3.0°	179.0°-180.0°	179.0°-180.0°
Varus group	52	179.0°	3.0°	172.0°-185.0°	178.0°-179.5°
Valgus group	27	180.5°	2.0°	178.0°-186.0°	180.0°-181.5°

Table 3 shows the bias (mean), imprecision (standard deviation) and precision (mean ± 2 standard deviations) for 180° HKA-angle. The mountain plots showed that 19% of the varus knee patients (Figure 1) had an outlier alignment over 177° and 11% of the valgus knees (Figure 2) an alignment over 182°.

Table 3 Precision of postoperative HKA-angle

Alignment	N	Mean	SD	Range	Mean + 2 SD
Total study group	83	2.0°	2.0°	0.0°-8.0°	6.0°
Neutral group	4	2.0°	3.0°	0.0°-6.0°	7.5°
Varus group	52	2.5°	2.0°	0.0°-8.0°	6.5°
Valgus group	27	2.0°	2.0°	0.0°-6.0°	4.5°

Table 4, 5 and 6 show the trueness for postoperative MPTA, LDFA and JLCA.

Table 4 Trueness of postoperative MPTA

Alignment	N	Mean	SD	Range	95% CI
Total study group	83	90.5°	1.5°	88.0°-93.0°	90.5°-91.0°
Neutral group	4	91.0°	0.5°	91.0°-91.5°	90.5°-91.5°
Varus group	52	90.0°	1.5°	88.0°-93.0°	90.0°-91.0°
Valgus group	27	91.0°	1.0°	88.0°-92.5°	90.5°-91.5°

Table 5 Trueness of postoperative LDFA

Alignment	N	Mean	SD	Range	95% CI
Total study group	83	91.0°	2.5°	80.5°-96.5°	90.5°-91.5°
Neutral group	4	86.5°	1.0°	89.5°-90.5°	89.0°-90.0°
Varus group	52	91.0°	2.5°	80.5°-96.5°	90.5°-91.5°
Valgus group	27	90.5°	2°	85.5°-94°	90.0°-91.0°

Table 6 Trueness of postoperative JLCA

Alignment	N	Mean	SD	Range	95% CI
Total study group	83	0.5°	0.5°	0.0°- 3.0°	0.5°-0.7°
Neutral group	4	1.0°	1.0°	0.5°-2.0°	-0.3°-1°
Varus group	52	0.5°	0.5°	0.0°-2.0°	0.5°-0.7°
Valgus group	27	0.5°	0.5°	0.0°-3.0°	0.3°-0.8°

The precision is shown for the overall study group in Table 7, for the varus group in Table 8 and for the valgus group in Table 9.

Table 7 Target, bias, imprecision and precision overall study group

	Target	Bias=Mean	Imprecision = SD	Precision = Mean + 2 SD	Range
MPTA	90.0°	1.0°	1.0°	2.5°	0.0°-3.0°
LDFA	90.0°	2.0°	2.0°	5.0°	0.0°-9.5°
JLCA	0.0°	0.5°	0.5°	1.5°	0.0°-3.0°

Table 8 Target, bias, imprecision and precision for varus group

	Target	Bias=Mean	Imprecision = SD	Precision = Mean + 2 SD	Range
MPTA	90.0°	1.0°	1.0°	2.5°	0.0°-3.0°
LDFA	90.0°	2.0°	2.0°	6.0°	0.0°-9.5°
JLCA	0.0°	0.5°	0.5°	1.5°	0.0°-2.0°

Table 9 Target, bias, imprecision and precision for valgus group

	Target	Bias=Mean	Imprecision = SD	Precision = Mean + 2 SD	Range
MPTA	90.0°	1.5°	1.0°	3.0°	0.0°-2.5°
LDFA	90.0°	1.5°	1.0°	4.0°	0.0°-4.0°
JLCA	0.0°	0.5°	0.5°	1.5°	0.0°-3.0°

Discussion

Neutral mechanical alignment in the coronal plane comes with a 180° HKA-angle. This study wanted to analyze the trueness of the 180° value as the true value that should be set as the alignment target. A preoperative HKA-angle of 180° was observed for neutrally aligned patients and of 178.5° for the total study group.

Postoperatively, a 180° HKA-angle could be observed for all different study groups with an error of 3° confirming the range accepted for neutral coronal alignment.

Bellemans et al. popularized the concept of constitutional varus with a mean HKA-angle of 178° as observed by Moreland et al. and Hsu et al. previously[4,9,10]. In this study, the overall HKA-angle was 178.5° with a 95% CI between 179°-180°. This confirms the trueness of 180° as the target for neutral mechanical alignment. The mean alignment was found to be 178.5° in the varus group and 180.5° in the valgus group.

The precision analysis of the HKA-angle showed a systematic error or bias of 2° with the same imprecision of 2° and a precision of 6°. The precision was better for the valgus group (4.5°) than for the varus group (6.5°). The fixed distal valgus cutting angle of 5° that was used in this patient population might influence this result since it favorizes valgus correction to neutral and might have undercorrected varus knees as we intended to do on the femoral side. This fixed distal valgus angle should be considered a systematic error with a bias of 2° since the mean distal valgus angle was found to be 7°.

The individual angles of the distal and proximal joint surfaces were also analyzed. For MPTA a trueness of 90° ± 1° was confirmed. For the LDFA it was 91°± 2.5° showing more imprecision at the femoral level. Trueness for JLCA was 0.5± 0.5° confirming good ligament balancing and gap kinematics. The precision for the femur (5°) was half that good as for the tibia (2.5°). Analysis of the outliers showed that femoral bowing, extra-articular deformities, small cortices at the isthmus with a wide medullar canal and different mediolateral positions of the distal femur to the diaphysis determine these outliers. This was observed more often for patients with varus disease over 10° (170° HKA-angle or lower). De Muylder et al. and Mullaji et al. observed the same difficulty to correct substantial deformities to neutral mechanical alignment[18,21,22].

The findings of this study with a precision of only 5° on the femoral side should stimulate surgeons to perform a preoperative planning and look on full leg radiographs for potential malalignment causes induced by anatomical variants[22-25]. In those cases extra-articular alignment options like accelerometers, computer navigation or patient-specific instruments (PSI) should be used. A recent meta-analysis by Thienpont et al. showed that PSI can be trusted for the coronal plane and that it obtains adequate HKA-angle corrections[14].

The controversy today is of course whether neutral mechanical alignment correction will help patients obtain better functional outcome[26]. Several authors observed good outcome with deformity undercorrection. Vanlommel et al. found better results in varus alignment patients with slight undercorrection. This finding could join the philosophy of constitutional varus for a segment of the population[8]. Howell et al. and Dossett et al. observed excellent outcome with kinematically aligned knees where valgus alignment was retained for the preoperative valgus knees[11,12]. In this study a fixed distal valgus cut angle of 5° was utilized to obtain undercorrection in the varus knees. A study by Innocenti et al. showed that undercorrection should be obtained at the femoral level and not at the tibial level[27]. Nam et al. and Maderbacher et al. showed the importance of measuring the individual valgus cut angle for each patient[28,29]. The precision found in this study, which was half that of the tibia, confirms these findings.

The importance of collateral ligament balancing and release of soft tissues to obtain good clinical outcomes becomes more and more clear. Tension in the collaterals determines potentially the outcome for patients[10,30-32]. The finding in this study that the JLCA was corrected to 0° with a precision of 1.5° showed that gap balancing was performed adequately.
One of the limitations of this study is that all measurements were performed on radiographs with a PAC System. Therefore we should wonder if the precision studied is an analysis of the surgical accuracy or the precision of the measurement process. The limitations of the intra-observer measurements were 1° and for test-retest it was 2°.
There are several other limitations to our study. The study results are
potentially limited by small sample sizes, but the proportion of patients
with preoperative valgus morphology in our study might be representative for
the proportion in the total population[33]. All of the procedures were performed by a single surgeon in a single institution. Consequently, the study findings are not readily generalizable. In addition, our results were not compared with those for other TKA systems or not compared to computer-assisted devices utilized by the same surgeon. The study analyzed therefore the repeatability of this technique but not its reproducibility.
The clinical importance of this study lies in the finding that with conventional instruments precision can be obtained. Variability is observed at the femoral level and more in particular in cases of substantial varus deformity. Individual distal femoral cutting angles should be determined by preoperative planning. Most of the residual deformities find their origin in femoral bowing or extra-articular deformities.
Conclusion of this study is that alignment-improving technologies can be important to correct the femoral component of deformity to obtain neutral mechanical alignment or the alignment the surgeon is aiming for depending of the peroperative target.

Figures

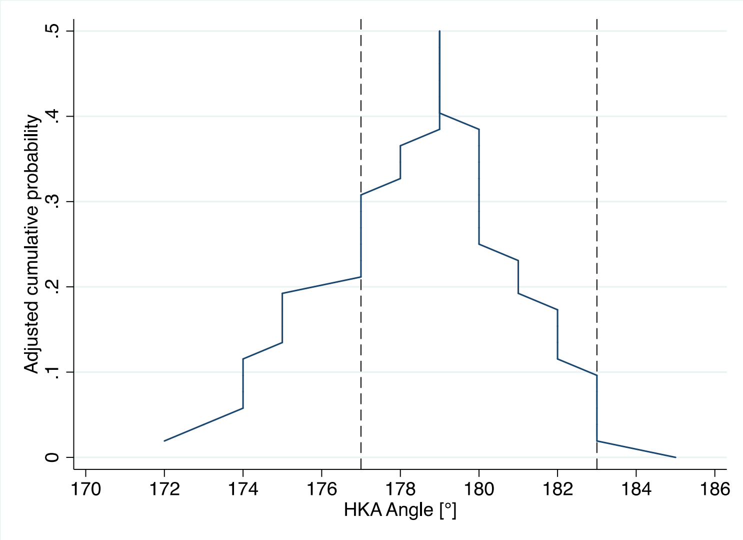

Figure 1 *shows mountain plot for varus alignment.*

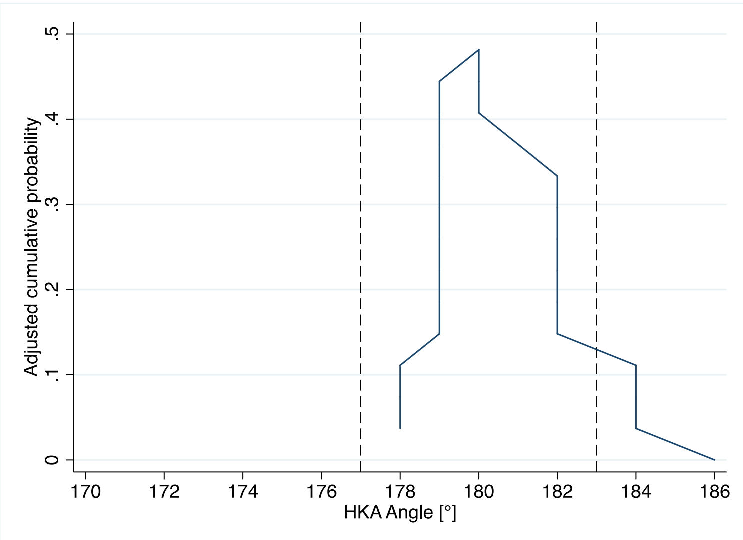

Figure 2 *shows mountain plot for valgus alignment.*

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Alignment in Total Knee Arthroplasty: Analysis of Surgical Accuracy

Chapter VIII: Can PSI increase surgical accuracy for coronal alignment?

Introduction

The postoperative outcome of total knee arthroplasty (TKA) with regard to functionality and pain is linked to patient satisfaction – with up to 20-30% of patients remaining dissatisfied after TKA[1]. Therefore, there is an urgent need to improve clinical outcomes.
The adverse impact of inadequate restoration of leg alignment on postoperative outcome has been a long-held tenet[2]. Implant malalignment is associated with TKA failure[3]. The commonly used surgical objective of TKA is therefore to restore neutral mechanical axis and alignment of the femoral and tibial components perpendicular to the mechanical axis of the leg. Thusly, implant alignment is imperative in total knee arthroplasty in the coronal, sagittal, and axial planes.
In an attempt to improve TKA outcomes, a recent technological advance is customization of instrumentation, i.e. patient-specific instrumentation (PSI). The goals of PSI utilization are to: improve the accuracy of implantation, reduce surgical time, and facilitate the workflow in the operating room[4]. To create PSI, magnetic resonance imaging (MRI), computed tomography (CT), and/or plain radiographs of the lower extremity are used by implant manufacturers to develop three-dimensional (3D) models of the patient's anatomy[5]. These models are then used to produce disposable pinning or cutting blocks to be used by the surgeon during TKA.
There has been an increase in PSI-assisted TKA worldwide since its inception despite the significant economic cost associated with the product[6,7]. This trend is likely associated with a perceived benefit of greater surgical accuracy or improved efficiency during arthroplasty[6]. Greater surgical accuracy includes improved implant alignment in the coronal, sagittal, and axial planes. In our paper entitled "Patient-specific instruments: industry's innovation with a surgeon's interest." we were able to show this continuous increase of PSI application without objective data being available to surgeons[6].
Following a random sample of studies, a systematic review and meta-analysis of the international literature was planned and conducted to evaluate PSI. The following are the results of a published study comparing PSI and conventional instrumentation in TKA.

Can PSI increase surgical accuracy for coronal alignment?

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(*Unedited, pre-publication draft utilized in PhD text*)
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Abstract

A meta-analysis, including randomized clinical trials (RCTs) and cohort studies, was conducted to examine the effect of PSI on radiographic outcomes: mechanical axis alignment; and malalignment of the femoral and tibial components in the coronal, sagittal, and axial planes, at a threshold of ±3º from neutral. Relative risks (RRs) for malalignment were determined for all studies, and for RCTs and cohort studies separately.
Of 325 studies initially identified, 16 met the eligibility criteria, including eight RCTs and eight cohort studies. There was no significant difference in the likelihood of mechanical axis malalignment with PSI TKA versus conventional TKA across all studies (RR=0.84, p=0.304), in the RCTs (RR=1.14, p=0.445) and in the cohort studies (RR=0.70, p=0.289). PSI TKA performed significantly worse than conventional TKA on tibial alignment in the coronal and sagittal planes (RR=1.75, p=0.028 and RR=1.34, p=0.019, respectively, on pooled analysis). PSI TKA showed a significant advantage over conventional TKA on femoral component alignment in the coronal plane (RR=0.65, p=0.028 on pooled analysis), but not in the sagittal plane (RR = 1.12, p = 0.437). Tibial and femoral axial alignment was not significantly different.
PSI does not improve the accuracy of component alignment in TKA over conventional instrumentation.

Introduction

The aim of total knee arthroplasty (TKA) is to restore neutral mechanical axis and to align the femoral and tibial components perpendicular to the mechanical axis of the leg. Mechanical limb alignment is the angle formed between the lines connecting the mechanical axis of the femur (centre of the hip to the centre of the knee) and the mechanical axis of the tibia (centre of the knee to the centre of the ankle). As the incidence of malalignment with conventional TKA, independent of surgeon experience, with conventional total knee arthroplasty (TKA) can be as high as 30%[8-11], there has been a great deal of interest in technologies that can help surgeons achieve a higher degree of accurate component alignment.
Patient-specific instrumentation (PSI) was recently introduced to improve implant alignment[12], with the aim of both improving surgical outcomes and reducing the risk of revision[13]. For this, magnetic resonance imaging (MRI), computed tomography (CT) and/or plain radiographs are relied upon by implant manufacturers to develop three-dimensional (3D) models of the patient’s anatomy. From these, disposable pinning or

cutting blocks are fabricated to help the surgeon reproduce the surgical plan during the surgical intervention.
Despite the theoretical advantages of PSI, there are a number of potential issues, such as the length of time required to manufacture the instrumentation[14], and the reliance on the same anatomical landmarks as conventional TKA[14]. Furthermore, the ability of an engineer to accurately plan a surgical case without the background clinical information remains to be established[15].
In order to justify the time and potential cost increases associated with a technique that seeks to shift the balance of surgical planning away from the individual surgeon to the implant manufacturer, PSI must be able to demonstrate significant and consistent advantages, particularly in terms of alignment, over conventional instrumentation in TKA. Previous investigations have indicated that results with PSI are not as reliable as might be expected, both in terms of component alignment and rotation[16,17]. Furthermore, significant changes to the surgical plan have been required in a substantial number of cases[15,17], and approximately one fifth of procedures with PSI had to be abandoned in one investigation[17]. While these issues would not necessarily be decisive for an experienced surgeon, they would be for surgeons inexperienced in TKA but attracted into performing TKA by the reassurances associated with PSI.
In a recent paper, alignment outcomes between navigation, PSI-assisted and conventional TKA were compared[18]. While navigation improved alignment accuracy versus conventional TKA, the findings were largely inconclusive for PSI and its assumed alignment advantages. It was clear, however, that we would have to wait for more data to become available to arrive at more definitive conclusions about this PSI technology.
With the publication in 2013 of a number of randomized controlled trials (RCTs)[16,17,19-24], and cohort studies[25-27], exploring outcomes with PSI in TKA, it was felt that an examination of all the available data to offer a pooled analysis of alignment outcomes was not only timely but also necessary.
We therefore conducted a systematic review and meta-analysis of alignment with PSI TKA versus conventional TKA in terms of overall mechanical axis alignment and individual component alignment on the coronal, sagittal and axial planes.

Materials and methods

We identified reports of studies that compared PSI TKA with conventional TKA, irrespective of the underlying condition. We included RCTs and non-randomized cohort studies with a minimal sample size of five. The decision to include non-randomized cohort studies was based on there being only a small number of relevant RCTs. To compensate for this[28], we opted to include non-randomized studies and, in addition to reporting the results combined across both study types, conduct a subgroup separate analysis for RCTs and cohort studies. The subgroup analysis was specified a-priori.

Eligibility criteria – inclusion and exclusion criteria
We adhered to the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) statement for reporting systematic reviews and meta-analyses in healthcare interventions[29]. Pubmed and EMBASE databases were searched for relevant studies up to 31 October 2013. No other data sources were consulted. Search terms consisted of MeSH headings and subheadings, text words and word variations for: “total knee arthroplasty”; “primary”; “patient specific instrumentation”; “patient matched instrumentation”; and “customized instrumentation”. There were no restrictions with

regard to the type of PSI used (i.e. manufacturer), the type of implant, or the operational approach followed. No language, date, or publication status restrictions were applied.

Data collection and quality assessment

Two investigators (PES and PF) critically and independently evaluated identified trials with regard to patient population, treatment, protocol, and endpoint selection. Divergences were resolved by consensus. Data were extracted from each eligible study by one researcher (PF) using a standard data extraction form. The following variables were abstracted: authors, publication year, study design, PSI system, gender, mean age, sample size, number of outliers of femoral and tibial components in each surgical plane, overall deviation from neutral alignment of more than 3 degrees, and methodology for determining malalignment.

The extracted data were independently reviewed by a second researcher (PES) to ensure accuracy. Each included study was assessed for methodological quality using a modified Detsky Quality Assessment Scale[30] by two reviewers (PES and PF). For the cohort studies, we added an extra item to assess the comparability of the cohorts on the basis of study design and/or analysis. The total possible score was 21. A study with a score of more than 75% of the total was considered high quality[30,31].

Interobserver agreement between the methodological quality scores was assessed using the intraclass correlation coefficient. Any disagreements between reviewers were resolved through discussion and, if required, with the assistance of the senior author (ET).

Study outcomes were mechanical axis alignment on standing full limb-length radiographs in full extension, and malalignment of the femoral and tibial components in the coronal, sagittal, and axial planes. As all the included RCTs used a threshold of ±3º from the intended position to define malalignment, this was chosen as the criteria for our analysis.

Statistical analysis

Contingency tables containing information on the incidence of malalignment were constructed for each study. Patients were analyzed 'as treated'. Relative risks (RRs) were calculated for mechanical axis malalignment and for malalignment of tibial and femoral components in the coronal, sagittal and axial planes; where an RR of 0–1 favors PSI, an RR of 1 suggests no difference between the two surgical approaches, and a RR >1 favors standard instrumentation. For the publication with zero events in both groups[16], each cell in the contingency table was inflated by adding 0.5.

We report the pooled RRs for each surgical plane, along with 95% confidence intervals (CI) and p values. We assessed heterogeneity with the Chi^2 test and the I^2 statistic[32]. For mechanical alignment, based on the observed heterogeneity, we used a random effects model developed by DerSimonian and Laird[33]. For the other surgical planes, we used fixed effect models based on those by Mantel and Haenszel[34], as the small number of studies in these planes made it impossible to estimate the between-study variance with acceptable precision. A sensitivity analysis was performed to assess the impact of this decision on study outcomes. In addition, we assessed the impact of study quality on outcome, with a subgroup analysis performed in which the grouping variable was binary variable study quality (i.e. dichotomized around the median value).

The risk of publication bias across the included studies was assessed using Harbord's modified test for small study effects[35], as well as a graphical assessment of the funnel plot, as described by Egger et al.[36].

All statistical analyses were carried out using Stata 12.1 (StataCorp, College Station, TX, US). P values of <0.05 were considered statistically significant throughout.

Source of Funding

No funding was obtained for this study.

Results

A total of 325 studies were identified in our initial search. Of these, 16 met the eligibility criteria (Figure 1)[16,17,19-27,37-41].

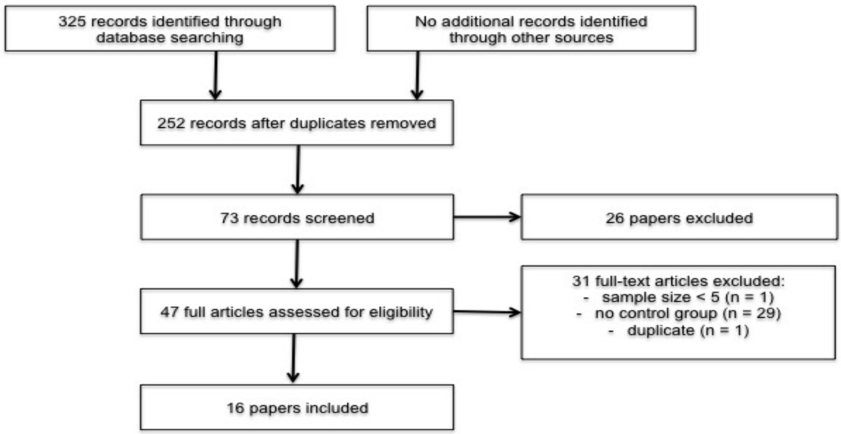

Figure 1 *Flowchart of RCTs and cohort studies identified for the meta-analysis.*

It should be noted that, of the 16 studies, two reported outcomes for the axial, but not the coronal plane[24,40]. There were a total of 1755 patients, 901 of whom underwent TKA with PSI and 854 who had conventional TKA. Eight RCTs were included in the analysis[25-27,37-41], with a total of 337 PSI TKA patients and 343 conventional TKA patients, alongside eight cohort studies, comprising 564 PSI TKA patients and 511 conventional TKA patients. Table 1 shows details of the included studies.
The intraclass correlation coefficient between the two reviewers was 91.9% (95% CI, 81.4–97.2%). The median score was 13. Of the 16 included studies, only four had Detsky Quality scores greater than 15, and could therefore be classified as being of high methodological quality.

Table 1 Characteristics of included studies and study treatments

Study	Design	System	N study group	N control group	Detsky Score
Bali[37]	Cohort	Visionaire*	32	6	10
Barrack[38]	Cohort	Signature‡	100	100	13
Barrett[25]	Cohort	TruMatch†	64	81	11
Boonen[19]	Randomized	Signature	86	82	14
Boonen[39]	Cohort	Signature	39	38	13
Chareancholvanich[20]	Randomized	PSI§	40	40	18
Chen[26]	Cohort	PSI	29	30	12
Chotanaphuti[21]	Randomized	TruMatch	40	40	18
Daniilidis[27]	Cohort	Visionaire	100	156	14
Hamilton[22]	Randomized	TruMatch	26	26	15
Heyse[40]	Cohort	Visionaire	46	48	11
Ng[41]	Cohort	Signature	105	55	11
Parratte[16]	Randomized	PSI	20	20	16
Roh[23]	Randomized	Signature	42	48	18
Silva[24]	Randomized	Signature	22	23	11
Victor[17]	Randomized	Misc.	61	64	18

* Smith & Nephew Inc., Memphis TN
‡ Biomet Inc., Warsaw IN
† DePuy Orthopaedics Inc, Warsaw IN
§ Zimmer Inc., Warsaw IN

Overall mechanical axis alignment

Fourteen studies in this meta-analysis reported alignment outcomes for the mechanical axis, including seven RCTs[16,17,19-23] and seven cohort studies[25-27,37-39,41]. There was no heterogeneity among the RCTs (I^2=0%, p=0.441), whereas the I^2 among cohort studies was 72% (p=0.001) and the overall heterogeneity was (I^2=58%, p=0.003). Looking specifically at RCTs, the RR for mechanical axis malalignment was 1.14 (95% CI: 0.82–1.57) (Figure 2). The RR was not statistically significant (p=0.445). In the cohort studies, the RR of malalignment was of 0.70 (95% CI: 0.42–1.17; p=0.289). There was no significant difference in the overall likelihood of mechanical axis malalignment with PSI TKA versus conventional TKA across all studies, at an RR of 0.84 (95% CI: 0.60–1.18; p=0.304).

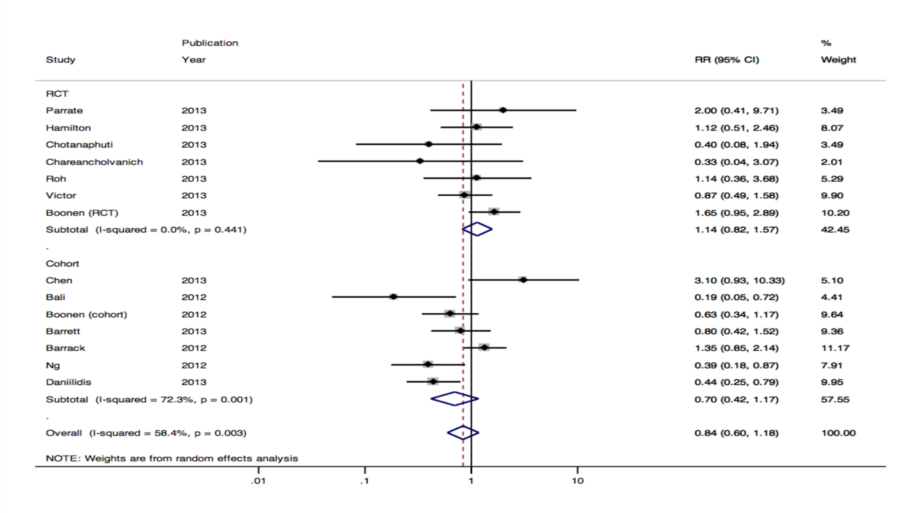

Figure 2 *Overall mechanical axis component alignment.*

Coronal plane

Eight studies reported outcomes for tibial alignment in the coronal plane, including five RCTs[17,19-23] and three cohort studies[26,39,41], giving a total of 427 PSI TKA patients (255 in RCTs and 172 in cohort studies) and 379 conventional TKA patients (260 in RCTs and 119 in cohort studies). Point estimates for the RR for the pooled estimate, and in the RCTs specifically, favoured conventional TKA over PSI TKA (Figure 3). In the RCTs, the RR of malalignment was 2.50 (95% CI: 1.16–5.36; p=0.019). The RR of malalignment among the cohort studies was 1.26 (95% CI: 0.65–2.47), but did not reach statistical significance (p=0.493). The overall pooled RR was 1.75 (95% CI: 1.06–2.88, p=0.028).

On the femoral side, the pooled estimate suggested a significant benefit in favour of PSI TKA (Figure 4). The RR of malalignment for PSI TKA versus conventional TKA in RCTs was 0.62 (95% CI: 0.38–1.04, p=0.07). In the cohort studies, the RR of malalignment was non-significant, at 0.69 (95% CI: 0.41–1.17, p=0.163). The overall pooled RR was 0.65 (95% CI: 1.06–2.88), which was statistically significant (p=0.028).

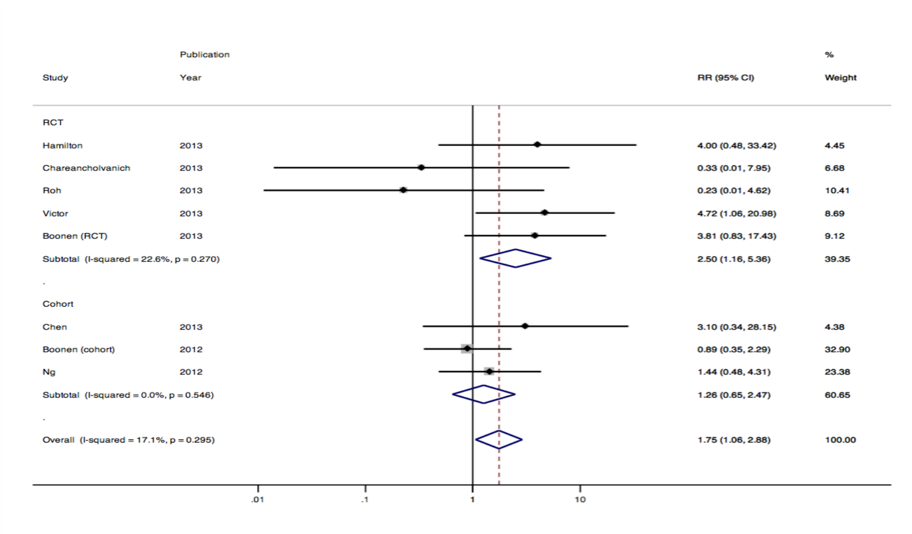

Figure 3 *Tibial component alignment in the coronal plane.*

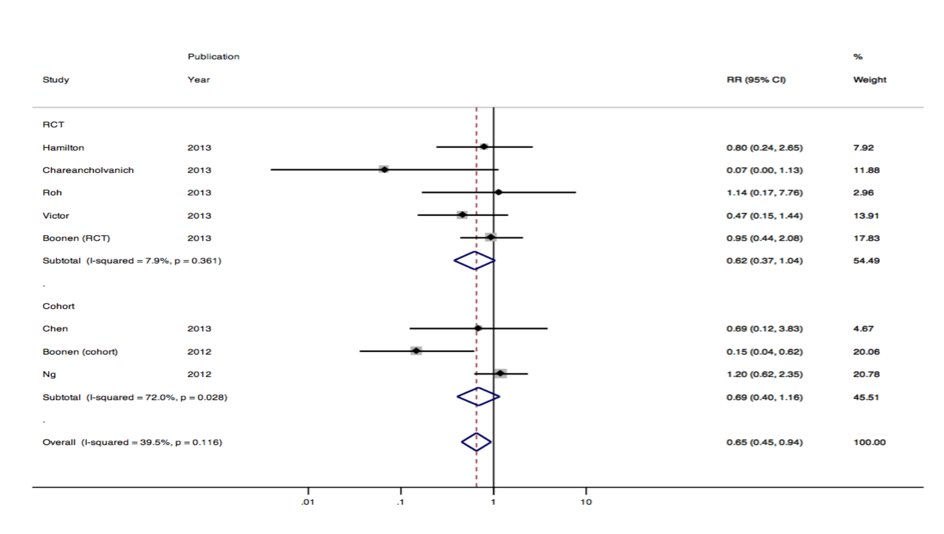

Figure 4 *Femoral component alignment in the coronal plane.*

Sagittal plane

Six studies, including four RCTs[17,19,22,23] and two cohort studies[26,39], reported outcomes for the sagittal plane, with a total of 283 patients who had PSI TKA (215 patients from RCTs and 68 from cohort studies) and 288 who had conventional TKA (220 from RCTs and 68 from cohort studies).

With regard to the tibia, the point estimate for the RR for the pooled estimate favored conventional TKA over PSI TKA (Figure 5). The overall RR of malalignment among RCTs was 1.48 (95% CI: 1.07–2.05, p=0.018). In the cohort studies, the RR of malalignment was 1.13 (95% CI: 0.79–1.63; p=0.500). Combining RCT's and cohort studies, the RR was 1.34 (1.05–1.71, p=0.019).

There was no statistically significant difference in the likelihood of malalignment of the femoral component in the sagittal plane with PSI or conventional TKA for RCTs (Figure 6). The pooled RR of malalignment for RCTs was 1.12 (95% CI: 0.84–1.51; p=0.437). For the cohort studies, there was a significant decrease of the risk of malalignment (RR=0.56, 95% CI: 0.39–0.80, p=0.002), while the pooled RR for both RCTs showed a non-significant difference improvement for PSI (RR=0.87, 95% CI: 0.70–1.09; p=0.237).

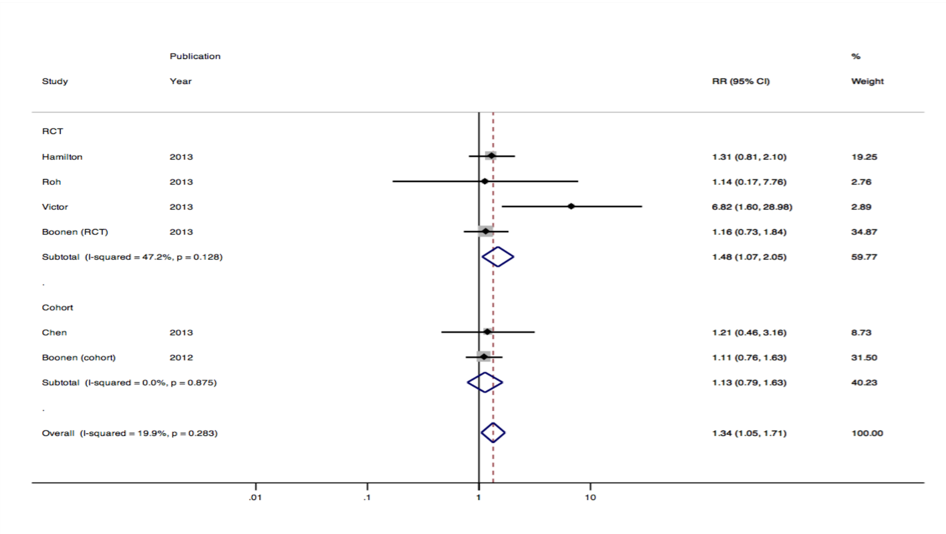

***Figure 5** Tibial component alignment in the sagittal plane.*

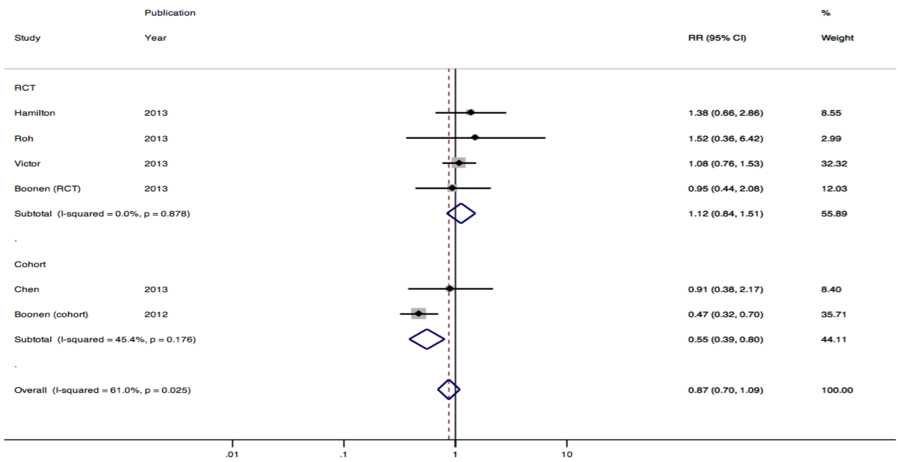

Figure 6 *Femoral component alignment in the sagittal plane.*

Axial plane

Only one RCT[24], comprising a total of 23 PSI TKA patients and 22 conventional TKA patients, and no cohort studies reported tibial component alignment in the axial plane. RR of malalignment was 0.77 (95% CI, 0.37–1.58, p=046) (Figure 7).

Malalignment of the femoral component on the axial plane was reported by six studies, including five RCTs[16,17,21,23,24] and one cohort study[40], with a total of 231 patients who had PSI TKA (185 patients from RCTs and 46 from the cohort study) and 243 who had conventional TKA (195 from RCTs and 48 from cohort studies).

The pooled estimate for RCTs showed no difference between the two groups (RR=0.97, 95% CI: 0.40–1.21; p=0.904). The single cohort study in the pooled analysis showed a large reduction of malalignment in the PSI group (RR=0.10, 95% CI: 0.01–0.71). The single cohort study has a large, albeit non-significant, impact on the combined RR of malalignment (RR=0.67, 95% CI: 0.40–1.21, p=0.127).

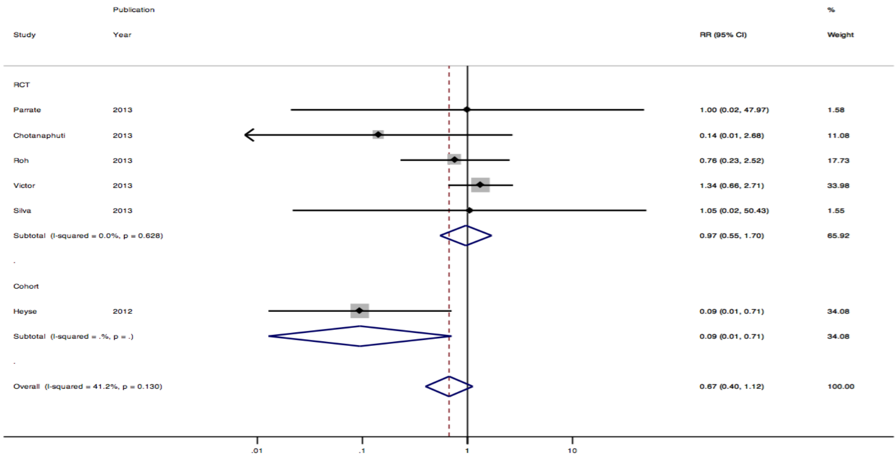

Figure 7 *Femoral component alignment in the axial plane.*

Publication bias

Visual inspection of the funnel plot produced for the studies reporting on the mechanical alignment shows no strong evidence of publication bias (Figure 8). The graphical appearance was confirmed by the statistical test (p=0.528). However, it is notable that three of the seven cohort studies[26,37,41] included in the analysis lay outside the lower 95% CI, suggesting a tendency to published more positive results than those seen in the overall body of evidence.

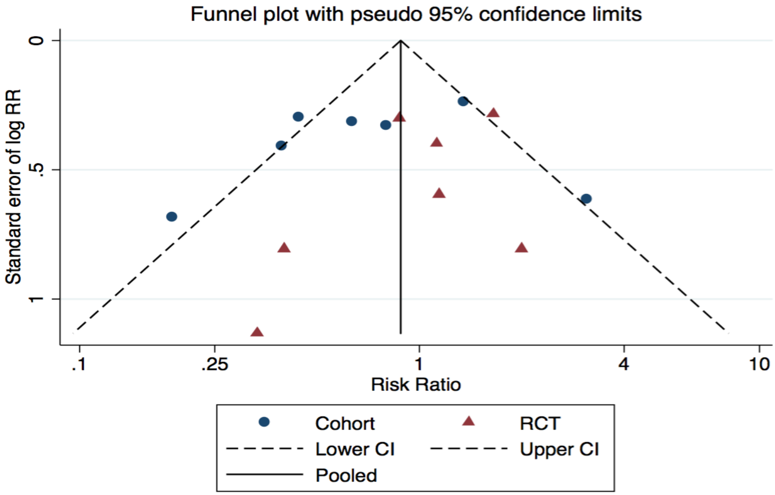

Figure 8 *Funnel plot of publication bias with pseudo 95% confidence limits.*

Sensitivity analysis

We performed a sensitivity analysis by applying random effect models to our data (Table 2, Table 3). Results from the sensitivity analysis showed that risk estimates were largely robust, but the statistical imprecision (as expressed by the confidence interval) consistently increased with the random effects model, leading to non-significance of the previously significant endpoints (Table 2).

Table 2 Point estimates and 95% confidence intervals obtained by fixed effect modelling

	RR	95% CI	p-value
Tibia			
- Coronal	1.72	0.92–3.19	0.089
- Sagittal	1.26	0.95–1.68	0.109
Femur			
- Coronal	0.66	0.38–1.14	0.137
- Sagittal	0.90	0.60–1.37	0.626
- Axial	0.61	0.23–1.59	0.310

Except for the sagittal femoral axis, estimates obtained in higher quality studies pointed in the same direction as the treatment effect in lower quality studies, although the latter were generally somewhat more optimistic for PSI (Table 3). Lower quality studies found a significant difference for axial femoral alignment (RR=0.14, p=0.007)[21,24,40], whereas the higher quality studies showed a pooled RR of 1.14 (p=0.68)[16,17,23].

Table 3 Point estimates and 95% confidence intervals stratified by study quality

	High Quality				Low quality			
	N	RR	95% CI	p-value	N	RR	95% CI	p-value
HKA Angle	7	0.90	0.68–1.19	0.45	7	0.86	0.66–1.12	0.269
Tibia								
- Coronal	5	2.50	1.16–5.36	0.019	3	1.75	1.06–2.88	0.493
- Sagittal	4	1.48	1.07–2.05	0.018	2	1.13	0.79–1.63	0.500
Femur								
- Coronal	5	0.62	0.38–1.04	0.070	3	0.69	0.41–1.17	0.163
- Sagittal	4	1.12	0.84–1.51	0.437	2	0.56	0.39–0.80	0.002
- Axial	3	1.14	0.62 – 2.06	0.679	1	0.14	0.03 – 0.59	0.007

Discussion

Despite intensive marketing campaigns from companies and a rapidly increasing worldwide proportion of TKAs performed using PSI, there is no compelling evidence from the published peer-reviewed literature demonstrating effectiveness versus standard instrumentation[6,18]. The current meta-analysis refutes the hypothesis that PSI offers advantages in terms of the relative risk of malalignment >3º on mechanical axis alignment. Most notably, a significant disadvantage with PSI TKA versus conventional TKA was found for tibial component alignment for both the sagittal and the coronal planes. On the femoral side, PSI TKA showed a significant advantage over conventional TKA on femoral component alignment in the coronal plane, and no statistically significant differences in the sagittal and axial planes.

For the coronal plane of the tibia, the results were robust: estimates for both RCTs and cohort studies pointed in the same direction, and there was limited heterogeneity across the studies. For the tibia on the sagittal plane, there were no studies showing a RR of malalignment less than 1 for PSI. However, the overall RR was influenced substantially by a single RCT that reported a RR of 6.8. Results for the femoral component showed a higher level of heterogeneity across the studies, predominantly caused by the non-randomized studies.

Comparing outcomes in RCTs with those from cohort studies, positive findings for PSI TKA versus conventional TKA were more commonly recorded in cohort studies. Whether this observation may have been caused by extrageneous factors – for example, cohort studies being conducted in early introducer centres in which experienced experts used the new technology, versus the more pragmatic designs of the RCTs – could not be determined. Nevertheless, the disparity between the RCTs and cohort studies serves as a reminder that we must ensure that the highest quality studies with the highest level of evidence form the basis of clinical decision-making.

The impact on implant longevity of the increased risk of malalignment for tibial components in the coronal and sagital plane with PSI remains an open question. Individual component malpositioning may lead to a higher failure probability, even if that is compensated for by the other component and the overall resulting mechanical axis is neutral[42].

This systematic review and meta-analysis was conducted in accordance with the PRISMA guidelines[29], and reliable conclusions on the efficacy of PSI could therefore be drawn for the first time.

The primary limitation of the current study is the paucity of eligible randomized clinical studies, for which reason we had to include observational trials with limited validity. We did not additionally search for grey literature or contact the authors of the individual papers for additional data. Beyond mechanical axis alignment, the data pool from which a comparison of alignment on the various planes could be made shrank substantially. Due to the small number of eligible studies, we used fixed effect models, which assumes that the treatment effect is the same across studies. In this particular case, with systems from different manufacturers in a variety of clinical settings, the assumption of homogeneity between studies is not tenable. The random effects models applied in the sensitivity analysis showed that our conclusions are robust, despite the added statistical imprecision causing a number of endpoints to change from significance to borderline significance.

A second limitation is that using mechanical alignment outliers as the endpoint has the disadvantage of variance in the methodology used to determine the endpoints in the different papers. For example, one study may have used CT scanning, while another used standard X-rays to examine alignment. However, any bias as a consequence of different measurement methodology is most likely to be non-differential, as the impact should be the same in both the PSI and conventional TKA groups. Another source of heterogeneity is that a different treatment effect has been measured over the different sites. Heyse et al. reported they did not have any cases where intraoperative adjustments needed to be made[40]. As part of their study, Chen et al. refrained from pre- or intraoperative adjustments to the operative plan proposed by the PSI manufacturer[26]. In other studies, however, manual adjustments were deemed necessary and performed[20,22,39]. If we assume that, with these adjustments, surgeons were able to prevent malalignment, the reported relative risk of malalignment may additionally shift in favour of standard instrumentation. However, we acknowledge that this assertion is largely untestable at present.

A third limitation of our study is that it relies on the concept of neutral alignment, the validity of which has been questioned. A recent study found that a substantial part of the population has a natural alignment of the lower extremity with a constitutional varus[43]. Another study found no association between residual component varus alignment and the risk of early loosening[44,45]. Kinematic alignment has been proposed as an alternative approach to neutral anatomic alignment, with excellent clinical outcomes[46]. Despite these ongoing discussions, there is little dispute that excessive malalignment should be avoided[42,47].

It is arguable that there are many measures other than component alignment that should be examined to determine the success of PSI TKA, such as operative time, instrument tray usage, clinical performance, transfusion rates, longevity and clinical outcome. However, the primary aim of the technique is to improve alignment. Furthermore, establishing the clinical impact of PSI TKA will take a great deal longer to assess than pure mechanical capability of the technique, and it is crucial that surgeons, both those of long-standing and their inexperienced colleagues, are furnished with as accurate a picture of its performance as soon as possible.

In conclusion, the current meta-analysis indicates that, overall, PSI does not improve the accuracy of component alignment in TKA over conventional instrumentation. In this meta-analysis better coronal alignment was observed for the femur. However, further studies will need to be conducted to examine the impact of the technique on clinical and patient-specific outcomes.

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Alignment in Total Knee Arthroplasty: Analysis of Surgical Accuracy

Chapter IX: Coronal alignment of patellofemoral knee arthroplasty

Introduction

Patellofemoral arthroplasty (PFA) has been gaining attention in recent years due to the development of second-generation prostheses and positive mid-term results[1,2]. Proven alternatives to total joint arthroplasty represent an important step forward for the more complicated cases of young patients with isolated patellofemoral arthritis. However, it is still unclear whether isolated PFA is more beneficial than total knee arthroplasty (TKA) for older patients.

Around 10% of patients with arthritis of the knee are affected by PF arthritis, and they are more likely to be younger and female[3]. Once non-operative measures have been exhausted, there are a number of options available for these patients. These include: lateral release, arthroscopic debridement, microfracture, mosaicplasty/autologous chondrocyte implantation, re-alignment, patellectomy, partial lateral patellar facetectomy, patellofemoral arthroplasty and TKA.

One of the difficulties facing clinicians dealing with patellofemoral pathology is that these younger patients have already had multiple surgical interventions prior to undergoing joint replacement[2,4]. For isolated lesions in certain parts of the patellofemoral articulation it can be possible to perform chondrocyte implantation, re-alignment procedures, microfracture or partial lateral facetectomy. However, if the disease has spread and is affecting both sides of the joint, these procedures are less likely to be successful[4]. In these cases PFA may be the best option.

Patellofemoral arthroplasty was first performed in the 1950s. McKeever described patellar resurfacing in 40 patients using a Vitallium prosthesis screwed onto the patella[5]. The next significant advance took place in the 1970s as Blazina et al.[6] and Lubinus[7] used femoral components in combination with the resurfaced patella. Their results were, however, marred by complications, high revision rates, and progression of arthritis, leading to revision to TKA.

The 1990s saw the advent of second-generation PFA designs[8-10]. Femoral components now had a broad, symmetrical trochlear flange that narrowed distally, allowing the patella to engage during flexion but be unconstrained in extension.

More recently, the third-generation of PFA has seen innovations such as a variable mediolateral breadth of the anterior flange that covers the anterior surface, increased proximal extension of the trochlear flange for onlay implants, a more accommodating sagittal radius of curvature, and a thinner femoral onlay component to avoid overstuffing[11,12]. Additionally, for some components, lateralized tracking angles have aided patellar tracking and reduced the need for lateral release[11,13].

There is now a greater awareness of how patellofemoral arthroplasty (PFA) outcomes are affected by rotational positioning of the trochlear components, and optimal positioning can be achieved with the latest techniques[11]. However, the varus-valgus positioning cannot be adjusted without consideration of anatomic features of each individual distal femur.

Coronal alignment of patellofemoral knee arthroplasty

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Abstract

Background: Patellofemoral arthroplasty (PFA) can yield successful results in appropriately selected patients. The varus-valgus position or coronal alignment of the trochlear implant is determined by how its transitional edges articulate with the condylar cartilage. Whilst variation in condylar anatomy will not influence the axis of the lower limb in PFA, it can impact the Q-angle of the PF joint. The aim of this study was to analyze how the coronal alignment can be influenced by the choice of anatomical landmarks.
Materials and methods: Retrospective analysis of 57 PFA with measurements of alignment on full leg radiographs.
Results: Coronal alignment following anterior condylar anatomy leads to a mean (SD) proximal valgus alignment of 100° (9°). Aligning the component with Whiteside's line gives a better alignment with less variance 89°(3°).
Discussion: A trochlear component with a higher Q-angle compensates for patellar maltracking if the condylar anatomy would tend to put the implant in a more proximal varus or neutral position. If the trochlear component is proximally aligned in valgus this may have the opposite effect. Aligning the trochlear component with the AP-axis in the coronal plane avoids maltracking and utilizes the design features of the implant at his advantage.

Introduction

Patellofemoral arthroplasty (PFA) was introduced in the late 1970's as a treatment for end stage patellofemoral osteoarthritis (PFOA)[14-17], but did not gain widespread use because of trochlear component design limitations that led to early mechanical complications like patellar maltracking, catching and subluxation[11,18]. Many of these early complications could be attributed to component malposition, soft tissue imbalance and improper surgical technique[11]. Second-generation PFA trochlear designs and improved instrumentation resulted in better outcomes in properly selected patients and led to improved insight into appropriate rotational alignment of the trochlear component[8-10]. Newer third generation designs have a more accommodating sagittal radius of curvature, a variable mediolateral breadth of the anterior flange covering the anterior surface, greater proximal extension of the trochlear flange for onlay implants and finally a thinner femoral onlay component to avoid overstuffing[11,12]. Furthermore, lateralized tracking angles of some components have also optimized patellar tracking and reduced the need for lateral release[11,13].
The importance of accurate alignment in all three planes of the knee is well proven in total knee arthroplasty (TKA)[19]. In PFA, appropriate rotational alignment, flexion-extension and translation are important determinants of patellar tracking which can be pre-selected, with relative independence of the native knee anatomy (particularly with some designs)[10,11]. In the coronal plane, the varus-valgus position of the trochlear

implant is influenced completely by the anterior condylar anatomy since its medial and lateral edges should be positioned flush with or recessed 1-2 mm from the neighbouring articular cartilage of the femoral condyles. For the second and third generations of PFA, instrumentation was developed to allow surgeons to position the implant according to the anatomical landmarks observed during surgery[11]. However, while there is improved understanding regarding how rotational positioning of the trochlear components impacts outcomes in PFA and newer techniques are available to achieve that positioning[11], the varus-valgus positioning is dependent on anatomic features of each individual distal femur and cannot be adjusted without consideration of those anatomic parameters.

The purpose of this study was (1) to determine the variability in coronal alignment of a third-generation onlay PFA trochlear design (Gender Solutions PFJ, Zimmer, Warsaw, IN, US) if the anterior condylar anatomy is followed; (2) to analyze if that coronal variability of the trochlear component can be reduced by following the anteroposterior (AP) axis of the femur (Whiteside's line)[20]; and finally (3) if coronal alignment would influence axial alignment of the patella and its tracking.

Patients and methods

Demographics

This retrospective study analyzed 57 Gender Solution PFJ (Zimmer, Warsaw, IN, US) implanted between January 2008 and June 2012 by one of the authors (ET). There were 36 women and 21 men with a mean (SD) age of 58.5 (10.5) and a BMI of 30 (5.5) kg/m^2. There were 24 left and 33 right PFA. There was a follow-up of 12 to 60 months with a mean (SD) of 24 (6) months. All patients had PFOA confirmed by either CT-arthrography or MRI and exclusion criteria were inflammatory arthritis, previous PF open surgery and infection. No PFA revisions were included.

Surgical technique

All 57 patients underwent a minimally invasive mini-parapatellar approach with implantation of a cemented Gender Solutions PFJ implant (Zimmer, Warsaw, IN, US) with resurfacing of the patella in all cases. The centromedullary hole was made in alignment with the distal femur in the lateral plane to follow the natural flexion of the femur. The anterior cutting guide was then aligned rotationally in the axial plane by using a combination of the Whiteside's line and the clinical epicondylar axis (CEA)[21,22]. Anterolateral notching was avoided by positioning the anterior boom on the anterior-most point on the lateral trochlear flange. Recuts can be made by gradually posteriorizing the anterior cutting guide to ensure that the cut is flush with the anterior femoral cortex. After the anterior cut the femoral size was determined with the milling guide looking at the mediolateral size and the distal position referenced off the intercondylar notch, with the objective of leaving a clearance of a few mm between the edges of the implant and the edge of the native femur and to avoid overhang into the intercondylar notch, which would result in anterior cruciate ligament impingement in extension. The intercondylar portion of the distal femur is prepared using a milling guide and burr. At this step the "feet" of the milling guide contact the articular cartilage and this orientation, which ensures that the trochlear component edges are flush with the articular cartilage, also determines its ultimate varus-valgus position (Figures 1a and 1b). At this stage one can often observe variability in varus-valgus position at the chondral surface, but the tracking angle of the implant will typically orient the prosthetic trochlear groove towards the lateral cortex to optimize patellar tracking.

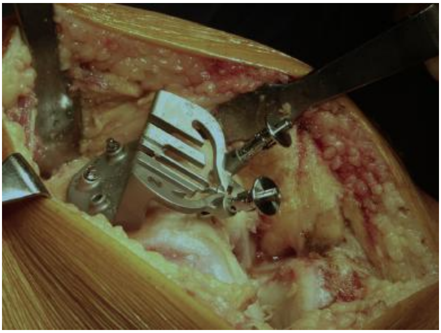

Figure 1a *Milling guide to prepare trochlear cartilage for PFA trochlear component.*

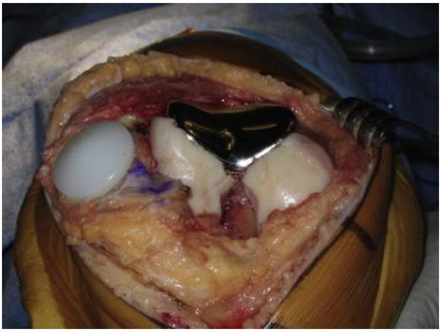

Figure 1b *Intra-operative photograph after trochlear component implantation showing its edges flush with the adjacent articular cartilage.*

Before 2011 the condylar anatomy was followed to position the femoral component, but from 2011 on in 23 patients, after having performed the anterior rotational cut, the trochlear implant was positioned according to the AP-axis independent of the condylar anatomy[20]. After the trochlear trial is positioned, the patella is resurfaced in a standard way. Patellar tracking was dynamically evaluated intra-operatively according to the criteria published by Akagi et al.[23]. Medial prosthetic contact of the patellofemoral joint through the range of motion was observed. It was noted if no thumb, one thumb or a lateral release was necessary to obtain sound patellar tracking [16]. Using this implant, no lateral retinacular releases were necessary except for one case. In that patient with a chronically dislocated patella correction of patellofemoral alignment was obtained by combining a realigning osteotomy of the tibial tuberosity with a lateral release and medial vastus advancement. The osteotomy was fixed with two screws and healed uneventfully. The postoperative protocol was identical for all patients. No drains were used. Rehabilitation and deep vein thrombosis protocol were identical as for TKA with full weight load bearing and walking without crutches and enoxoparin adapted to their weight once a day.

Trochlear Prosthesis Tracking Angle

To optimize patellar tracking, the Gender Solutions PFJ trochlear design features a 10-degree trochlear groove angle in the initial four sizes and a 7-degree groove angle for the largest size (which presumably would be used in larger men with a typically smaller Q angle). This enhanced tracking angle has proven particularly useful in female patients, who account for approximately two-thirds of PFA recipients and who often have an increased Q-angle, dysplasia and patellar subluxation preoperatively, and in all patients due to the variability in condylar anatomy.

Data Analysis

Preoperatively and after one year postoperatively, patellar tracking was assessed clinically and radiographically and Knee Society Scores were collected. Preoperative and postoperative range of motion was noted. Any complications were recorded in the study protocol.

Peri-operative tracking of the patella, presence of trochlear dysplasia, tourniquet and surgical times and lateral release rates were observed. Transfusion rate and hospital stay were also recorded.

All patients had full leg standing radiographs performed pre-operatively and at one-year follow-up and standard radiographs to evaluate osteolysis or loosening of components. The full leg radiographs were performed in a standardized way controlling rotation of the lower limb by a few standing flexion-extension movements of the knee assuring the patella was facing the X-ray beam. All measurements were performed with the PACS (Carestream, Health, Rochester, US) by one observer (ET) who repeated the measurements three times. Mean (SD) intra-observer variation on measurements was 1° (0.5°). First the rotational position of the full leg radiograph was confirmed by looking at the central position of the patella. The femoral anatomical axis was determined as a line in the middle of two proximal cortical points and the middle of two distal cortical points of the femur letting it run distally through the centre of the knee. Then a tangent to the distal femur was drawn and the lateral angle between both was measured as the anatomical Lateral Distal Femoral Angle (aLDFA-femur). On the same full leg radiographs the mechanical axis defined, as the centre of the femoral head and the centre of the knee was determined. Then the tangent to the distal femur was drawn and the lateral angle between both measured as the mechanical LDFA (mLDFA-femur) (Figure 2)[24,25].

Figure 2 *shows the mLDFA of the right femur and the aLDFA of the left femur.*

Two distal points on the distal aspect of the PF implant (tangent) were chosen and the angle between the anatomical axis was measured on the lateral side as the aLDFA-implant and between the mechanical axis as the mLDFA-implant (Figure 3).

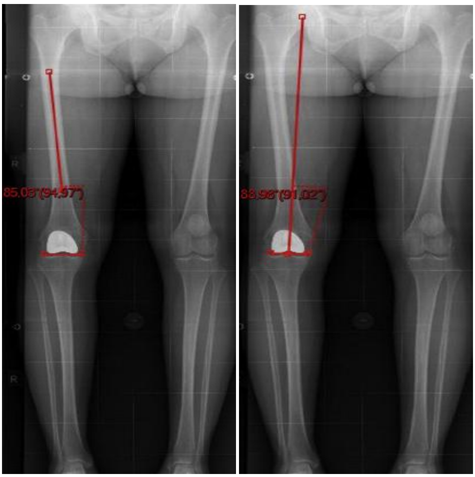

Figure 3 *shows the aLDFA on the right femur of the left figure and the mLDFA of the right implant on the right figure.*

The position of the femoral implant was described as being distally in varus resulting in a more proximal and laterally oriented trochlea, pointing lateral to the centre of the femoral head or distally in valgus resulting in a more proximal medially oriented trochlea pointing medial to the centre of the femoral head or central if it was in a neutral position (Figure 4).

Figure 4 *shows the three potential coronal positions of a trochlear component; either proximally in valgus (left), central (middle) or proximally in varus (right).*

On the full leg radiographs the weight bearing alignment (HKA-angle) according to Moreland et al.[26] and the angle between the anatomical and mechanical axis (AMA) was measured (Figure 5).

Figure 5 *shows mechanical alignment of the left lower limb and angle between anatomical and mechanical axis (AMA) of the right femur.*

On the Merchant view radiographs the patella was classified statically as central, tilted, subluxated or dislocated according to Schutzer et al.[27] and lateral tilt of more than 10° or patellar displacement of more than 4 mm was considered misalignment according to Heesterbeek et al.[28] Radiolucent lines on the patellar or femoral components were classified according to the Knee Society Radiological Score if present[29].

Ethical approval was obtained by the University hospital St. Luc, Brussels; Belgium (CEBHF 2012/03 MAI/2013).

Statistical Analysis
Data are represented as numbers, means and standard deviations. The normal distribution of the data was assessed by the Kolmogorov-Smirnov test. Statistical analysis was performed with Wilcoxon - Mann-Whitney *U* test for independent samples. Student *t* test used for dependent samples. Comparison of observed proportions was performed using Chi-square and Fisher's exact test for categorical data. Pearson correlation was determined if indicated. All differences were considered significant at a probability level of 95% (P<0.05). Analyses were performed using SPSS (Chicago, US) version 16.

Source of Funding
No external funding was used in support of this study.

Results

Retrospective analysis showed that the Knee Society Score (KSS) for function improved from 45 (20) to 90 (10) as well as the KSS for pain that improved from 45 (10) to 85 (10). Mean (SD) extension was 0° (4°) and flexion 142° (15°) at one-year follow-up and had improved from -2° (5°) extension and 128° (12°) preoperatively. One patient had Persistent Post Surgical Pain (PPSP) and two patients had a squeaking knee. Both of these patients had a proximal valgus position of the trochlear implant.
Intra-operatively all patellae were tracking centrally without a thumb except one who needed the only lateral release of this series and an associated tibial tuberosity osteotomy for chronic dislocation. Trochlear dysplasia was present for 30 patients. Tourniquet time was 23 (9) minutes and total surgical time for PFA was 40 (11) minutes. No transfusions were performed. Mean (SD) hospital stay was 3 (1) days until return to their home.
The preoperative alignment measurements and results are given in Table 1. For the group until 2011, ten of the thirty dysplasia patients had a distal varus position of the trochlear implant with a mean (SD) proximal open valgus angle of mLDFA 100° (9°). Radiological analysis of the implants showed no osteolytic lines or fractures of the patella. The Merchant view showed 51 patients with a central patella position. Two patients had a lateral tilt (Figure 6) and four patients a lateral shift of the patella (Figure 7) according to Heesterbeek et al.[28].

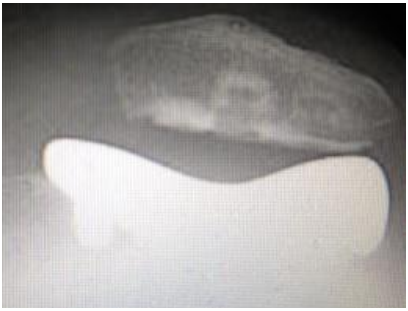

Figure 6 *shows lateral tilt of patella on Merchant view of PFA.*

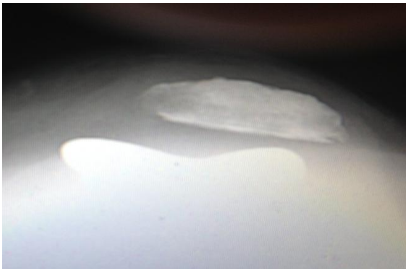

Figure 7 *shows lateral shift of patella on Merchant view of PFA.*

The mean (SD) lateral overhang of the lateral facet was 4 (2) mm. These were all female patients with a size 2 or 3 femoral component and a mean 10° (4°) proximal valgus position of the trochlear component. No dislocations were observed.

Table 1 Preoperative and postoperative alignment measurements

Measured Parameter	Mean (SD) Angle in °
HKA-angle	179° (1°)
Anat – Mech Axis (AMA)	7° (2°)
mLDFA Femur	87° (3°)
aLDFA Femur	81° (2°)

The 23 patients aligned with the AP axis in the frontal plane had a central position of the implant on full leg alignment measurements with the distal part of the trochlear component perpendicular to the mechanical axis mLDFA-implant 89° (3°) and aLDFA-implant 83° (2°) varus position from the anatomical axis of the femur. None had tilt or shift on the Merchant view.

The mean (SD) angle between the anatomical axis (aLDFA-implant) and mechanical axis (mLDFA-implant) of the femur is given in Table 2 and compared for group PFA before 2011 where the condylar anatomy was followed and group PFA after 2011 where the

AP-axis was followed for coronal alignment. For the latter group the variance was importantly reduced.

Table 2 Axis between trochlear implant and mechanical and anatomical axis femur

	PFA before 2011	PFA after 2011	P value
mLDFA Implant	93° (10°)	89° (3°)	0.17
aLDFA Implant	87° (9°)	83° (2°)	0.045

Discussion

We observed in this study that the anatomic variability of the distal trochlea and condylar surfaces influences coronal alignment of the trochlear component in PFA. Unlike TKA, where a conventional distal condylar resection is performed irrespective of condylar shape or alignment, based on a preset valgus angle, the coronal alignment of the trochlear prosthesis in PFA is influenced by the local condylar anatomy at the interface with the prosthesis, and this alignment may have an influence on patellar tracking, especially from extension to early flexion. The implications can be particularly problematic with internally rotated or anteriorized and symmetric components with a neutral tracking angle. The trochlear tracking angle of the implant referenced in this series optimizes patellar performance and accommodates the observed variability in condylar anatomy by directing the proximal extent of the groove laterally[30] what should be helpful in case of proximal varus alignment of the trochlear component.

The modern PF implant studied here has an increased tracking angle built in to accommodate female anatomy, with its commonly increased Q-angle. This may reduce the impact of trochleo-condylar anatomic variation, which could predispose to patellar catching or maltracking[8,13] with proximal varus of a non-optimized component. Less well understood is whether a trochlear implant in too much proximal valgus could lead to increased pressures between the patella and the lateral wall of the trochlea[31] and predispose to polywear or loosening. Because of the optimized tracking angle of the implant too much proximal valgus because of condylar anatomy of the patient can have an influence on the patellofemoral tracking in deeper flexion[32]. Furthermore external rotation of the femoral component induces more valgus alignment[33,34].

Iranpour et al. found that the line along the deepest points of the trochlear groove was aligned 1° ± 5° in valgus relative to the transcondylar axis corresponding more or less to the mechanical axis[35]. Therefore aligning the trochlear implant with the AP-axis[20] seemed an adequate solution for coronal positioning of a PFA. However, given the condylar variability and the need to position the transitional edges of the implant flush with the adjacent articular cartilage may ask sometimes for some compromise in position. The difficulty in coronal alignment of the PFA is that the angle is not determined by intra-medullary alignment referencing of the femoral anatomical axis, with a relatively standard and reproducible valgus angle of 5-7 degrees, but instead it is based on the distal trochlear and condylar anatomy and how the edges of the implant interface with the surrounding articular cartilage. Trochlear component designs should have an enhanced tracking angle and asymmetry to accommodate this variability. With the implant studied here, coronal alignment variability had no influence on axial patellar

tracking or the need for lateral release. This differs from one of the author's experience with other symmetric or inlay-style implant designs[10,11].
In this study we found no negative influence on axial patellar tracking with variations in coronal alignment using a third generation onlay style asymmetric trochlear prosthesis with an optimized tracking angle with an incidence of lateral retinacular release less than 2%. Lateral tilt and shift of the patella was observed on the proximally valgus aligned trochlear components. These findings suggest that femoral trochlear rotation determines axial alignment of the patella and coronal trochlear alignment determines tilt and shift of the patella.

Conclusion

Positioning a PFA is a delicate procedure and aligning the implant correctly in the three planes is a challenge. Following the condylar anatomy can lead to a more proximal valgus or varus position of the trochlear component depending of the case. The increased Q-angle in the implant compensates for a potential proximal varus position allowing good PF tracking. Additionally, as with all trochlear components in PFA, aligning the implant perpendicular to the AP-axis[19] reduces the variance of coronal alignment and seems a good compromise for this implant with an increased Q-angle.

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Chapter X: General discussion and conclusion

Neutral mechanical alignment is the coveted objective of total knee arthroplasty (TKA), which aims to address the varus or valgus deformity present in knees with osteoarthritis (OA)[1]. The required constraint that the implant provides, differs according to the extent of deformity, surgical technique, and choice of implant[2].
The overall mechanical alignment in Caucasians is slightly varus with a joint line parallel to the floor[3-3]. Additionally, at least one study of radiographic evaluation of knees revealed that the majority of patients showed the same alignment for both knees, and more often for varus deformity than for neutrally aligned or valgus knees[4].
Historically, neutral coronal alignment has been linked to implant survival, but this factor may be less crucial given the advances in implant design and bearing materials[5-8]. Recently, coronal alignment and individual positioning of components have been given greater focus for improved results, with attention given to both anatomical and kinematic alignment[9-15].

Coronal alignment is an important factor for TKA outcome, it may however not be the sole determinant and may only contribute to failure from other causes[10]. Sagittal and rotational alignment, joint line restoration, and soft-tissue balance are all important considerations for TKA. To further complicate outcomes, a recent study of kinematic alignment showed that alignments for patient function and implant survival may differ[11]. Prosthesis longevity may persist functionally, but not in an optimal mechanical environment. In consideration of another factor affecting TKA outcome, varus of the tibial component may impact survivorship more than a mild residual global varus deformity[11,12].

Hence we conclude that the concept of a more anatomical alignment has not matured yet. There is a paucity of clinical evidence on safety and efficacy, and the little evidence available comes from observational studies from which robust conclusions cannot be drawn. This is reflected in the survey that was presented in Chapter 3. Surgeons still deemed mechanical alignment of the knee as highly important, with primary objectives including a joint line parallel to the floor and a centrally running load-bearing axis. Only a few surgeons evaluated their surgical result with postoperative full leg radiographs and HKA-angle measurements[13].
Unicompartmental knee arthroplasty is probably an elegant surgical solution to recreate the native gait cycle and to reconstruct the anatomy as physiologically as possible. UKA still remains controversial, as we were able to proof in this survey article. In one of the questions, we asked the 300 surgeons if they would prefer UKA or TKA for themselves in case of anteromedial osteoarthritis. A majority of surgeons (87%) wanted UKA for their own knee. However if they were to select the best treatment for their own patient around 9% of those same surgeons would implant a TKA. This difference in choice can be explained by the dilemma of adequate treatment choice and the question whether we want a patient specific treatment adapted to its specific problem or if a surgeon specific treatment, like a TKA, would be proposed[14]. When a surgeon selects UKA for himself, he has less to worry about the factors that potentially would lead to UKA failure[15].

He can select his colleague, who will operate on him, with inside information about both quality and quantity[16,17]. He knows for himself that he wants this treatment and won't complain to his colleague about his well-informed and personally made choice[18]. Indicating UKA to a patient can be difficult because it asks for a complete understanding of the knee problem. The disease process and patterns of wear should be analyzed and linked to the overall alignment of the limb[19,20]. Other criteria to help with patient selection are the integrity of the ligaments, flexibility of the other joints, the age of the patient, bone quality, flexion deformity, co-morbidity and the global health status of the patient. Is unicompartmental arthroplasty a choice for the young and active, often called a step-up operation, or is it the one and only intervention to be foreseen for that patient[15]. The difficulty of UKA, even when performed in the right patient, is that it exposes us to peer pressure. What is the UKA culture of the surrounding colleagues[16]? The threshold of revising a UKA is much lower than for a cemented rotating hinge[18]. By performing a UKA we allow other surgeons, often with less experience with the implant, to decide about the quality of our work, often based on the idea that half an implant is less worth than more metal. Concepts like persistent post-surgical pain, neuropathic pain, referred pain or overload pain in the medial compartment are often forgotten and revision for unexplained pain leads rarely to better outcomes[21-24]. Coronal alignment should be considered as one of the limitations when choosing between UKA or TKA.

For substantial varus or valgus deformities, good TKA outcomes can be achieved using a combination of a minimally invasive far medial subvastus approach, interchangeable posterior stabilized (PS) implants, and soft tissue release with a piecrust needling technique. In Chapter 4, our hypothesis was confirmed that substantial deformity in the coronal plane couldn't only be corrected by a LDFA (lateral distal femoral angle) and MPTA (medial proximal tibia angle) correction. As such, deformities with >10° of mechanical malalignment can be treated with primary implants when:

- The approach does not destabilize the soft tissue sleeve;
- Releases are titrated with a needling technique; and
- The primary implant allows for full interchangeability of femoral and tibial sizes.

Additionally, PROM (Patient-Reported Outcome Measure) scores were higher for undercorrected varus alignment patients. In a study of patients with substantial deformities, excellent postoperative mechanical alignment was achieved via a minimally invasive far medial subvastus approach and an interchangeable PS implant, even though a significant proportion of the study cohort (28%) showed >3º deviation from neutral alignment. Using this approach, most study patients did not have radiolucent lines after surgery, and average clinical outcome scores were higher for the undercorrected varus knees than for the 180° HKA (hip-knee-ankle)-aligned knees. These results suggest good clinical outcomes and patient satisfaction, along with the fact that no patients required revision surgery. Further study has also shown that undercorrection of major knee deformity resulted in better clinical outcome for patients[25]. The mean Forgotten Joint Score-12 (FJS-12) of the patients in the current study[26] was higher than the score for a normal control in the index study on the FJS-12 from Behrend et al.[27]. This indicates that the relative realignment of severe deformities results in a greater likelihood that patients are able to forget about a joint as a result of successful treatment as compared to the bad mechanical situation they had experienced preoperatively.

The observation of the inability to correct lower limb deformity despite of correct component placement led to the intra-articular angle analysis explained in Chapter 5.

We observed that the combination of these different anatomical angles shows us our potential of correction. If the deformity is outside those limits, residual deformity will remain measurable on the full leg radiographs.

The understanding of the impact of intra-and extra-articular deformity as well as soft tissue contracture or laxity lead to the development of a new and unedited classification of varus knee deformity as shown in Chapter 6. With this new classification system, surgeons can aptly prepare for an individual patient's TKA by selecting the appropriate implant and eventually the correct degree of constraint[28]. The classification makes a distinction between intra-articular and extra-articular deformities as well as the flexibility of the deformity. Knee osteoarthritis with varus deformity is the most common form of bone-on-bone arthritis. Similar to Krackow valgus classification[29], this proposed classification is an organized approach to varus pathology to make prospective studies and treatment options available to surgeons performing TKA.

With the understanding of the anatomical variants and disease processes leading to deformity we also wanted to understand how able we would be to correct this measured deformity. In Chapter 7, we analysed both varus and valgus deformity patients leading to the understanding of pre-deformity alignment for both groups and the reason 180° HKA was selected as the target for neutral mechanical alignment. Once this value was set it is important to study how true and precise this value can be obtained and therefore how accurate conventional instruments might be. If conventional instruments would be disappointing, innovation and technology should help us to reach our targets with a minimum of errors, especially reducing the systematic errors of instrumentation.

In Chapter 8, the benefits of patient-specific instrumentation (PSI) were analyzed. While PSI was not found to reduce the risk of malalignment of the mechanical axis significantly, it did improve femoral component placement in the coronal plane. The risk of individual component malalignment was otherwise not improved through the use of PSI. The risk of tibial component malalignment was almost 30% greater for PSI as compared to the risk of malalignment using standard instrumentation in both coronal and sagittal planes. In part due to the paucity of studies, PSI did not show efficacy in the axial plane or with surgical accuracy despite the large number of TKAs that have been implanted with PSI. In a systematic review of published meta-analyses, surgical navigation showed significant risk reduction of malalignment in the coronal and sagittal plans, with relative risk ratios below 0.5[30], as compared with standard instrumentation. In our meta-analysis, we found a non-significant risk reduction (16%) of risk of mechanical plane alignment and no consistent alignment advantages for implant component alignment. Tibial component malalignment appears to greatly affect TKA outcome. In an assessment of the impact of malalignment on the tibial and femoral components, changes in tibial component alignment, in both varus and valgus directions, produce a higher level of contact stress and pressure[12] and more failures when compared to changes in alignment of the femoral component[31]. Furthermore, when femoral components compensate for a varus or valgus orientation of the tibial component, this leads to a significantly increased failure rate of 3.2% to 7.8%[31]. Further studies will be needed to evaluate tibial component malalignment on long-term implant survival.

While technical advances are needed to improve functional outcome of TKA and increase implant survival, the associated clinical benefits need to be analyzed against incremental costs and risks. As our meta-analysis showed, PSI only had a minimal effect on surgical precision and clinical effect awaits further supporting evidence. In our most recent meta-analysis, we included functional outcome scores, blood loss and surgical time. The results on alignment remain comparable as for our previous one, but furthermore no clinical significant differences could be found. Not for the reported outcome scores, not for the difference in surgical time (4 minutes), not for the difference in blood loss (35 mL)[32].

Finally, after heaving measured intra-articular anatomy of the distal femur and proximal tibia in our study groups, we realized that for some types of surgery no corrective osteotomy of the femorotibial bones is included in the surgical technique. Therefore in Chapter 9 the hypothesis that coronal alignment is not important in implants that don't have a distal femoral cut can be refuted. In patellofemoral arthroplasty, the articular margins of the trochlear anatomy determine the position of the femoral implant. The proximally valgus-aligned trochlear components showed lateral tilt and shift of the patella. As such, it appears that femoral trochlear rotation determines axial alignment of the patella and coronal trochlear alignment determines tilt and shift of the patella.
Coronal alignment of the trochlear component in PFA is influenced by anatomic variability of the distal trochlea and condylar surfaces. In TKA, a conventional distal condylar resection is performed regardless of condylar shape or alignment, and is based on a preset valgus angle (Valgus Correction Angle between the anatomical and femoral mechanical axis). In a study by Merican et al., the trochlear tracking angle of a specific implant optimized patellar performance and adequately accommodated the observed variability in condylar anatomy by directing the proximal extent of the groove laterally[33]. This type of implant would be helpful in case of proximal varus alignment of the trochlear component.

The findings of this doctoral thesis made us realize that deformities bigger than 10° of mechanical axis deviation are difficult to correct with the intra-articular osteotomy that we call TKA. In the varus knee important deformity is usually on the femoral side and in the valgus knee at the diaphyseal level of both bones with a medial translation of the knee center. Furthermore we observed in our accuracy study of conventional instruments, that the precision on the femoral side was half that of the tibial side. However in PSI the coronal plane of the femur was the only area of interest for PSI. Therefore we would conclude that all three-plane alignments were and are important and that substantial alignment corrections (>10°) should be performed with some type of accuracy improving technology, allowing extra-articular alignment independent of the anatomical femoral axis. We could imagine that within the preoperative deformity planning of the surgeon, a deformity bigger than 10° mechanical axis deformity, would lead to the decision of utilizing PSI on the femoral side or some similar technology.
Especially, if we would decide to aim for specific alignment targets closer to the previously described failure areas, some kind of technology should make the surgery more repeatable and more reproducible if we want it to impact the total cost of health care.

Conclusion

In summary, coronal alignment of the knee has been underrepresented as an important component of knee arthroplasty, and in the future may be found to be a crucial factor in all types of knee arthroplasty outcomes.

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Chapter XI: Future Perspectives

Performing scientific studies about coronal alignment of the knee and the accuracy of surgical alignment, with the need for precise radiological measurements and the intrinsic precision limitations of the surgical procedure, is very confronting for a researcher[1]. While running this type of studies we are continuously confronted with the limitations of our potential as human beings and scientists.

First of all, we are measuring radiographic alignment on a PAC System with its own limitations of accuracy as well as the limitations of the human eye to determine the individual anatomic landmarks[2]. For example, determining the centre of the hip or the centre of the knee is a variable. We were able to study this variability and with training and experience to reduce it to a test-retest error of 1° and an inter-and intra-observer error of 1°. However that is only the data acquisition part, intrinsically considering that each radiograph was executed under the same exact conditions, both in the same patient preoperatively and postoperatively, as well in the different patients of each study group. Previous research has shown that alignment will differ under weight-bearing and non-weight-bearing conditions[2]. Furthermore, we are all aware that on full leg standing radiographs the impact of rotational deformities can not be corrected, leading to a certain bias in our findings[3]. It was only by consistently trying to perform the measurements as good as possible and reperforming them in case of doubt that we could come to the collection of this data. An intrinsic problem of radiographic studies is the repeatability and reproducibility of the technique.
Within the hypotheses of this study we had to distance ourselves from the impact of the other alignment planes on our measurements. Varus and valgus deformity will differ depending on rotation and flexion deformities whenever present. Today, implementing corrections in the coronal plane for the impact of the other alignment planes is only possible with the use of CT-scan. However exposing big patient groups to preoperative and postoperative CT-scan, might be difficult ethically. As long as clinical outcome improvements are not observed with better alignment accuracy, the first adagio of medicine “primum non nocere” must preside in research too. A potentially innovating technique for this type of studies would be the utilization of the EOS stereo-radiographic technology (Paris, France). This technique allows for 3D radiology without the burden of high radiation doses[4,5]. However, we have to realize that the rotational influence on full leg radiographs measurements depends on the anatomical-mechanical valgus angle (AMA) of the femur. With an AMA of about 7°, which is the mean for the Belgian population, the rotational error can be up to 30° before it induces an error of 1°. With an AMA of around 5°, as in the Asian population, we can accept up to 40° of rotational mistake[6]. It can therefore be discussed if the investment to buy this new technology is worth the inaccuracy that could occur.

Secondly, we are analysing static alignment of the knee. We include the hip and ankle but only as measurement landmarks. Coronal alignment measurements with the ankle as a reference might be a limiting constraint to the accuracy we observe. We were not able to analyse ground reaction forces of the calcaneus. All of us are load bearing on their calcaneus and not with the centre of the talus, which is utilized as the reference for Hip-Knee-Ankle angle measurements[7]. The analysis of static alignment is probably a good start to understand the mechanics of joint line positioning but is of course too basic to help us understand the full clue of patient satisfaction and limb alignment[2,8]. Future perspectives should include dynamic alignment looking at the gait pattern of a patient with his own patient-specific way of moving and load transmission. We should analyze the different angles that allow the knee joint to remain parallel to the floor despite of his deformity[9]. Furthermore we should be able at some stage to evaluate the joint before substantial deformity is present or simulate the anatomy as it was before the osteoarthritic deformity occured[10].

Because of research and innovation new technologies will develop and these should focus on the acquisition of 3D data of the gait pattern of patients and their dynamics of walking. They should simulate the pre-disease process and show if this patient had a normal gait pattern or not before recreating his patient-specific pattern. A pool of gait patterns for the normal population should be available.
We should determine what our target for alignment will be and how accurately we can recreate this with the instruments available at that moment. A new technology should allow us to consistently repeat the same objective with a precision within 1° allowing us to recreate individual joint line angles or positions of individual components. This technique should also be reproducible allowing other surgeons to obtain the same results.

Robotics that seems to be the newest hype in arthroplasty surgery starting its business cycle now[11] has a sense if the margin of error will become so small that it beats the repeatability possibilities of even the most experienced surgeon. The same applies of course if the experience of surgeons will go down and more surgeons would do less cases asking for a technique with better reproducibility. Or if the robot allows for new, more advanced and precise cutting techniques superior to the bias of hand-held power engines[12].

All of the above should be developed after we were able to prove that the functional outcome and satisfaction of the total knee patient is improved with a certain alignment technique. At the end of the day, we are responsible to our society to deliver the best possible healthcare at an affordable price[13].

As we wrote in our editorial in 2013[14], this is a challenging topic with many open issues. We hope that this doctoral thesis will contribute to the advancement of knowledge. But we still believe that everything is not said about coronal alignment and that many other studies shall and should be performed in the future at the benefit of our patients.

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Alignment in Total Knee Arthroplasty: Analysis of Surgical Accuracy

Summary

In this doctoral thesis the focus has been on coronal alignment of the knee. Initially, alignment was linked to survival of components but once this problem seemed to be solved, alignment was related to functional outcome and patient satisfaction. The observation that component positioning to obtain neutral mechanical alignment would lead to changes of the intra-articular joint line anatomy lead to different hypotheses about optimal knee alignment.

In a first study of this doctoral thesis we surveyed the opinions of knee surgeons around Europe and we observed that most stick to mechanical alignment principles despite that they don't measure their preoperative and postoperative alignment for resource reasons. Therefore they are exposing themselves to the impact of extra-articular deformities on their surgical technique or on their postoperative alignment result.

In a second study we found that mostly extra-articular deformities and femoral bowing complicate the correction of substantial deformities. An analysis of intra-articular anatomy and the potential for correction showed that both the distal femoral, proximal tibial and joint congruency angle are limitative factors for correction. If deformity overrides the potential of correction, residual deformity will be observed despite of correct component positioning. The better understanding of both intra-and extra-articular deformity, lead to the creation of a new varus knee classification. Once deformity and correction are understood, we should analyze how accurate our surgical procedure is in obtaining the aimed for results. Trueness and precision was measured for conventional instruments but accuracy of new technologies was also analyzed by performing a systematic review and meta-analysis about patient-specific instruments and their help in obtaining accurate cuts and neutral mechanical alignment.

Finally, coronal alignment was analyzed for an implant type that doesn't correct the distal femoral anatomy but utilizes trochlear anatomy to obtain varus and valgus alignment of its trochlear component.

It was the aim of this doctoral thesis to improve the knowledge about coronal alignment of the preoperative and postoperative knee.

Samenvatting

In deze doctoraatsthesis ligt de focus duidelijk op het frontaal alignement van de knie. Initieel werd alignement verbonden aan de overleving van het implantaat maar eens dit probleem opgelost leek, werd alignement verbonden aan de functionele uitkomst en de tevredenheid van patiënten. De observatie dat component positie om een neutraal mechanisch alignement te bekomen tot een hele boel veranderingen van de intra-articulaire anatomie leiden, inspireerde chirurgen tot verschillende hypothesen over het optimale alignement van de knie.

In een eerste studie werd in deze doctoraatsthesis een groep Europese knie chirurgen ondervraagd en we observeerden dat de meesten onder hen de principes van neutraal mechanisch alignement hanteerden, desondanks dat ze noch preoperatief noch

postoperatief hun alignement nakeken met aangepaste röntgenopnamen omwille van economische redenen.
Hiermee stellen ze zichzelf bloot aan de impact van extra-articulaire afwijkingen op hun chirurgische techniek of hun postoperatief alignement resultaat.
In een tweede studie vonden we dat de correctie van belangrijke afwijkingen vooral moeilijk is in aanwezigheid van extra-articulaire afwijkingen. Een analyse van de intra-articulaire anatomie en het potentieel tot correctie toonde aan dat zowel de distaal femorale, proximaal tibiale en gewrichtslijn congruentie hoek limiterende factoren tot correctie zijn. Van zodra de opgemeten afwijking het potentieel tot correctie overstijgt, zal een residuele afwijking geobserveerd worden, ondanks het correct plaatsen van de individuele componenten. Het begrijpen van zowel intra- als extra-articulaire afwijkingen leidde tot het creëren van een nieuwe classificatie voor de varus knie. Eens de afwijking en correctie begrepen werden, dienden we te analyseren hoe accuraat onze chirurgische procedure wel is in met het oog op het behalen van goede resultaten. Consistentie en precisie kunnen bepaald worden voor conventionele instrumenten maar ook de accuraatheid van nieuwe technologieën dient geanalyseerd. Dit gebeurde door middel van een systematische review en meta-analyse van patiëntspecifieke instrumenten en hun hulp in het behalen van accurate zaagvlakken en een neutraal mechanisch alignement.
Tenslotte, werd het frontaal alignement bestudeerd voor een implantaat dat de distale femorale anatomie niet corrigeert, maar de trochleaire anatomie gebruikt om varus en valgus alignement te bepalen voor zijn femorale component.
Het was het doel van deze doctoraatsthesis om de kennis in verband met frontaal alignement van de knie te bevorderen, zowel in de preoperatieve als postoperatieve faze.

Acknowledgments

Scientific work is often considered as something awkward by many of us. They state that it is just nothing for them and that they are not really interested in it. All of us involved in research, while having a full time clinical job, know exactly what they talk about. We have the same feelings when we are tired or going through difficult times. We know the painful feeling of writer's block with clear ideas in our mind but difficulties to put them on paper and the struggle with a language that is not our mother tongue. However for some strange reason some of us override these feelings of yielding and keep fighting our inner voices of minimal effort. What is the trigger leading to all this? No one probably really knows, but the wish to better understand and to have answers to questions, is certainly one of the reasons. I often thought it was less frustrating to search for the answers myself than to wait for someone else to give them to me. The drive to figure it all out, being clearly more burning than the wish to chill out.

When I decided, quite soon during my residency program that I would specialize in knees, I remember to have reflected by myself that so much was known and written about the knee and knee arthroplasty in particular, that I would never be able to add the smallest detail to this segment of orthopedics. But the more we specialize in something and the better we understand the job we do, the more questions arise. And after experimenting and looking for answers, we sometimes find them. Publishing is nothing more or less than communicating with our colleagues across the world and helping them to advance thanks to the knowledge we obtained.

Clinical research in knee surgery is not like searching for a solution for cancer, but with the growing number of cases being operated every year, making each knee arthroplasty patient a little better, remains a noble cause. We can only do today our outermost best and tomorrow others will evaluate that best for its value. As Francis of Asisi said "Start by doing what's necessary, then do what's possible and suddenly you are doing the impossible". That is what I do, for those who continuously ask me how I am able to combine it all. I just do what is possible, nothing more...

Performing this doctoral thesis with Jan Victor and Johan Bellemans seemed so logic to me. I started my orthopedic career still as a medical student working with Jan. When he left the KU Leuven, Johan took over the department and I performed the bigger part of my residency with him. Combining these two surgeons in one project was a great moment and closes the circle that started 20 years ago. Since Jan became the head of orthopedics at Ghent University, it became obvious to perform my doctoral thesis here.

I want to thank Ghent University for giving me this great opportunity.

A diversity of degrees from different universities makes me a real example of the true Belgian. I became a medical doctor and surgeon at the KU Leuven. I obtained my Master of Business Administration (MBA) at the UC Louvain, the same university where I work as a knee surgeon today. Finally, I will have a doctoral degree in Health Sciences from the Rijksuniversiteit of Gent. Different languages and moralities combined that are representative of the complexity of this fabulous country.

I want to thank the chair Prof. C. De Wagter and all the members of the jury for taking the time to read my work and especially for their great suggestions in making it better.

It is an honor to have Prof. W. Fitz with us from Harvard, Boston. Wolfgang understood quite soon that conventional total knee is disappointing a certain segment of patients

and this helped him to push the boundaries of knee surgery. It is also a pleasure to have Prof. JN. Argenson from Marseille, France here today. Jean Noel is truly the pope of European arthroplasty surgery and the bridge between European and American arthroplasty schools. A bridge across the ocean we might say[1].

I want to thank of course my colleagues of the knee team that I lead in Saint Luc hospital because both Arnaud and Delphine make it possible for me to keep finding an interest in getting to work every day. Our interactions about difficult patient cases and new surgical techniques make this job worthwhile.

I want to thank my colleagues from the orthopedics department of Saint Luc who are always there and many are able to keep me realizing what medicine is all about. Special thanks to Olivier Cornu who is always supporting me throughout difficult days and of course Christian Delloye who convinced me to come to Saint Luc.

I want to thank the nurses from the operating room under the lead of Dominique to have patience with me on days when I was facing another deadline or received another critical review from a paper. The same thank you goes out to the nurses of our ward under the lead of Marie France and the team of the outpatient clinic, who take such good care of our patients. And finally, I want to thank the anesthesiologists always available for a funny discussion across the blood-brain barrier. We all know knee arthroplasties don't bleed…

I want to thank Isabelle and Dali and all our secretaries for solving our daily administrative problems allowing us to think about quality patient care and science.

I want to thank Peter Fennema who was my statistical and methodological support. Our discussions late at night over the phone about statistical parameters and significance were and will always be enlightening.

I want to thank Pierre Emmanuel for all the work he did. It has been a pleasure to have someone to count on, someone who commits and delivers, which is rare in today's society. I saw in you one of our team members, but you see it bigger and will go work in the US. I am sure you will be adding some European flavor to the American orthopedics world.

I want to thank Aurelie and Samy our research students for their dynamics and daily assistance. Good luck with your medical careers.

Finally, I want to thank my family. My parents for giving me my genetics needing only a few hours of sleep and having me shown that working is important. I guess, also for making me believe there is nothing else than medicine in life… After six generations of doctors I hope someone in our family will be smart enough to change profession. This brings me to my three terrific children who are so wonderful and are convinced that all dads on this planet work 20/24 hours... And last but not least, my wonderful wife who is the best mother our children can wish, a master organizer for our family and the stable ground everyone needs in his life. As a wise man once said. "Marriage is like exchanging your own bike for a tandem bicycle." From that day on you have to cycle together. The secret in selecting your partner is to find the one who doesn't fight you to take the handle bar when you want it, who takes it when she should and to know that you don't need to check behind your back if she is pedaling too. It allows you to stay focused on the road ahead and to avoid the hazards on the highway of life. For those who were asking how I do all that I do…it's because she does all the rest.

I want to thank everyone who came to this public defense because in life we don't remember days, but we remember moments and the people we shared those with.

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Emmanuel Thienpont
Brussels, Belgium
12 October 2016

Curriculum vitae – Publication list

THIENPONT EMMANUEL

Education

HUMANITIES Sint Jan Berchmans College Brussels
graduated with greatest distinction in Latin-Mathematics

1995 Medical doctor (MD) graduated with great distinction
at the Catholic University Leuven (KUL)

1995-2001 Orthopaedic surgeon residency UZ Pellenberg, KU Leuven

2010 Executive MBA, Louvain School of Management, UCL, Belgium

Professional experience

2003-2005	Orthopaedic surgeon HF-CDP-ULB, Brussels
2005-2008	Head of orthopaedic surgery, Hôpital Français-ULB, Brussels
2006	Part-time consultant knee surgery Saint Luc, Brussels
2008	Full time appointed University Hospital Saint Luc, Brussels
2012	Louvain School of Management (Executive MBA) co-teacher
2013	Appointed Professor Catholic University of Louvain (UCL)

Actual function

Head of Knee Surgery & Sportsmedicine
University Hospital St. Luc, Brussels, Belgium

Professional associations and functions

Instructional Course Lecturer AAOS since 2007

Instructional Course Moderator AAOS since 2013

Instructor at Current Concepts of Joint Replacement (CCJR) since 2015

Board member (Treasurer) of European Knee Association (EKA)

Founding and Board member (Treasurer) of European Knee Society (EKS)

Founding member and Vice-president of CAOS Belgium (CAOS BE)

Board member of Belgian Knee Society (BKS)

Board member of Orthopaedics Today (OTE)

International Member of the American Knee Society (AKS)

List of recent peer-reviewed publications

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2. Emmanuel Thienpont, Author

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Meeting organizer or program chair

The European Consensus Group Meeting 2016 & 2015 Brussels, Belgium

The Partial Knee Meeting 2016 & 2014 Knokke & Brussels, Belgium

BVOT Knokke CAOS BE session 2016 Knokke, Belgium

Transatlantic Orthopaedic Congress 2016 & 2015 New York, US

The Knee^2 – International Knee Meeting 2015 Gotheborg, Sweden

Recent Advances in Knee Surgery 2013 Prague, Czech republic

Recent international lectures

AAOS, New Orleans, US 2014
Invited ICL speaker on revision knee arthroplasty

ESSKA, Amsterdam, The Netherlands 2014
Invited ICL speaker on Rapid Recovery programs

EFORT, London, UK 2014
Invited speaker on PSI and organizer symposium on bicompartmental arthroplasty

CAOS International, Milan, Italy 2014
Invited key note speaker on PSI

South African Knee Society and South African National Congress, Cape Town, SA 2014
Invited key note speaker on PSI

Polish National Orthopaedic Meeting, Wroclaw, Poland 2014
Invited key note speaker on Rapid Recovery and revision knee arthroplasty

The London Knee Meeting, London, UK 2014
Invited speaker on PSI/bicompartmental knee arthroplasty

ISTA Meeting, Kyoto**,** Japan 2014
Invited speaker on PSI

ISK-ICJR Transatlantic Meeting, New York, US 2014
Invited speaker on Rapid Recovery and patellofemoral arthroplasty

Vreden Meeting, Saint Petersburg, Russia 2014
Invited speaker on bicompartmental arthroplasty

Chinese Orthopaedic Association, Bejing, China 2014
Invited speaker on alignment in knee arthroplasty

AAOS, Las Vegas, US 2015
Invited ICL speaker on revision knee arthroplasty

World Arthroplasty Meeting, Paris, France 2015
Invited speaker on pain in knee arthroplasty

Efort, Prague, Czech Republic 2015
Invited ICL speaker on alignment in unicompartmental knee arthroplasty and patient matched knee arthroplasty

Belgian – Dutch Knee Society Meeting, Amsterdam, The Netherlands 2015
Invited speaker on prevention of infection in knee arthroplasty

Transatlantic Orthopaedic Congress, New York, US 2015
Invited speaker on Rapid Recovery and painful knee arthroplasty

Vreden Meeting Saint Petersburg, Russia 2015
Invited speaker on alignment and stability in knee arthroplasty

CCJR Orlando, US 2015
Invited speaker on unicompartmental arthroplasty and revision knee arthroplasty

AAOS, Orlando, US 2016
Invited ICL speaker on revision knee arthroplasty

EFORT, Geneva, Switzerland 2016
Invited ICL speaker on revision knee arthroplasty

The Great Debate, London, UK 2016
Invited speaker on unicompartmental knee arthroplasty