Restoring anatomy with TKA:

from bone to soft tissue

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Prologue

The project of this thesis was born during a hard ski journey with my supervisor, Prof. Jan Victor, in January 2012. While climbing the slopes, we couldn't refrain from debating around our passion, knee biomechanics and knee prosthesis, and from arguing about the possibilities to go back to sport after knee prosthesis. In the warm evening of the hotel, around a huge 'Swiss Fondue', we planned to do several investigations and I am extremely grateful to Prof. Victor who invited me to conduct all the experimental researches in his department at the University of Ghent. After one year working with an enthusiastic team in Ghent University, we were able to finalize a unique protocol to investigate the implant-soft tissues interactions in total knee prosthesis. Three years later, following several nights in the laboratory of anatomy and in the radiology department, carrying heavy specimens from one facility to the other, we obtained enough data to validate our hypotheses.

I would like to warmly acknowledge Prof. Tom Van Hoof, who was deeply involved in the day and night laboratory work, Prof. Katherine D'Herde, Chair of the Anatomy and Embryology department who managed the logistics, Dr. Wouter Huysse, who helped obtain the MRI and CT-scans and particularly, Dr. Catherine Van Der Straeten, who organized the sessions, the connections and the practical details, including the night catering! Data analysis, manual segmentations, conception of dedicated software and mathematical measurements required a weekly or daily link between Ghent and Lyon teams and all that work would have been impossible without the great contributions of Matthias Verstraete (MEng) and Arnoud de Kok (MD). At the same time, morphometric analysis of the human knee was conducted from my patients' CT-scan database, with a close collaboration between Ghent and Lyon. I

would like to acknowledge Yannick Carrillon (MD) who did the CT scans used in these morphometric studies and Mo Saffarini (MEng) for his unique input in the CT analysis.

It is worth noting that much of the reflections that went into this work are the result of the influence of my two main mentors, Professors Henry Dejour and Pierre Chambat who instructed their fellows to carefully evaluate surgical results and to learn from our failures, in order to improve our procedures. The stimulating debates that we have weekly inside the Lyon School of Knee Surgery push all of us toward permanent questioning and also to look ‘outside of the box’ and all these investigations reflect somewhere a collective evolution in which each of us brought his part. Therefore I acknowledge my contemporaries of the Lyon School of Knee Surgery.

Above all, I must thank my family, which provided much inspiration and encouragement. My parents, both mathematics professors and researchers, stimulated my scientific mindset and curiosity since childhood. My wife, Hélène, gave me daily support during all these years of additional work and should be thanked for sharing my interest in phylogenesis of the popliteus tendon, and for visiting museums of natural history worldwide, just to take pictures of archaic knees. Lastly, I also thank my two beloved children William and Charlotte to have the good idea to never sprain their knees!

CONTENTS

Summary in English

TKA is one of the most successful procedures in modern surgery, largely used in case of severely damaged knees, with nowadays 100 to 250 implantations each year per 100.000 inhabitants in western countries. Despite this tremendous success, 10% to 25% of the patients remain unsatisfied with the procedure, mostly due to residual pain or to functional limitations. In our investigation conducted among 347 patients with unilateral uncomplicated TKA, 68% of the patients reported that their operated knee was "strictly normal", 66% responded that they were as active as they expected to be before the intervention – of them 98% were satisfied – but 56% responded that their activities were still limited by their knee – of them 52% were not satisfied with their outcome. While standard radiographs rarely reveal abnormalities in painful TKAs – hence euphemistically named 'unexplained pain' in medical literature – taking care of these patients is a great challenge. The literature reveals that factors associated with a more painful knee prosthesis include female gender, a younger age at the time of surgery, and a higher than normal depressive or anxiety state. In particular, the Pain Catastrophizing Scale (PCS) appears to significantly influence patients outcome after TKA. However, such psychological speculations should not overshadow physicians' responsibilities to identify hidden mechanical explanations. Surgeons should keep in mind that 'unexplained' pain does not mean 'unexplainable' pain, but mostly 'not-yet understood' pain. The aims of this thesis were to understand why some apparently well-implanted TKAs remain painful and to investigate the responsibility of bone-implant mismatch and soft tissue impingements in these residual pains. We hypothesized that slight anatomic mismatch – lack of restoring native anatomy – may explain at least a part of these residual pains.

In a continuous series of prospectively followed patients with TKA, we demonstrated that oversized components appear to be an under-recognized cause of residual pain. CT-scan measurements showed a mediolateral prosthetic overhang in at least one area in 66% of the

femurs and in 61% (mediolateral) to 87% (anteroposterior) of the tibias. The pre- to post-operative improvements of the pain and function scores were significantly greater in patients without overhang, when compared to patients with overhang. Regression and latent class analysis showed a significant negative correlation between general oversizing and global outcomes. Such a high rate of bone-implant mismatch can be explained by human anatomic variations and by surgical techniques. From this CT-scan database, a detailed morphometric analysis was conducted at the level of the standard TKA bone cuts and the native bone morphologic characteristics were compared to those of TKA models. The influence of surgical technique on bone-implant fit was also investigated. (1) Tibial plateaus morphology varies considerably depending on the rotational axis used. The choice of aligning the tibial component with the posterior tibial margin, the trans-epicondylar axis or the anterior tibial tuberosity axis should influence the component design. It should also allow some variation if surgeons wish to optimize simultaneously prosthetic coverage and alignment with the extensor mechanism. The study emphasizes the great variation in tibial plateau morphology, with up to 17% of patients having a reversed asymmetry (lateral greater than medial) and illustrates that custom implants could be beneficial for extreme cases of asymmetry. (2) Concerning the morphology of the distal femur, the newly defined 'trapezoidicity' ratio revealed that 'rectangular-trapezoidal' variability of the distal femur should not be ignored. Most prosthetic overhangs were observed in trapezoidal femurs and most of the tested femoral implants appeared to be excessively rectangular when compared with the bony contours of the distal femur. (3) We investigated the dimensions of the posterior condyles and the influence of externally rotating the femoral component on potential prosthetic overhang or under-coverage. External rotation amplifies the asymmetry between the medial and lateral condyles, and exacerbates prosthetic overhang, particularly in the supero-lateral zone.

Finally, aiming to improve our understanding of soft tissue-implants interactions, an in vitro imaging protocol was developed, usable throughout the range of motion, and potentially with different kinds of prostheses. Using this newly defined protocol, the pre- and post-operative positions of the popliteus tendon were compared from full extension to deep flexion using normo-sized, over-sized and under-sized implants. This experiment demonstrates that a well-sized tibial component modifies popliteal tracking, while an undersized tibial component maintains more physiologic patterns. The data also demonstrate that oversizing the tibial component by one-size increment shifts the popliteus considerably throughout the full arc of motion.

The findings from the series of studies presented in this thesis confirm the existence of considerable anatomic variations in human knees that are not matched by contemporary TKA designs. The resulting prosthetic overhang and/or under-coverage are a common cause of soft-tissue impingements that result in residual pain and compromise knee function. Surgeons should beware of the consequences of bone-implant mismatch in order to prevent, diagnose and treat soft-tissue impingements. Manufacturers should also acknowledge the anatomic variations in order to enhance the design of their implants and instruments to anticipate and avoid prosthetic overhang without compromising bone coverage and implant fixation.

Summary in Dutch

Totale Knie Artroplastiek (TKA) als behandeling van eindgradige knieartrose, is een van de meest succesvolle operaties in de hedendaagse chirurgie in de westerse landen, met een prevalentie van 100-250 implantaties per 100.000 inwoners per jaar. Ondanks dit enorme succes blijft 10-25% van de patiënten ontevreden met de procedure, meestal ten gevolge van residuele pijn of functionele beperkingen. In ons onderzoek, uitgevoerd op 347 patiënten met een unilaterale ongecompliceerde TKA, melde 68% van de patiënten dat hun geopereerde knie "helemaal normaal" was, 66% antwoordde dat ze de vooraf verwachte activiteitsniveaus aankonden – onder hen was 98% tevreden - maar 56% antwoordde dat hun activiteiten nog steeds beperkt waren door hun knie - onder hen was 52% niet tevreden met de uitkomst. Terwijl de standaard röntgenfoto's zelden afwijkingen onthullen in pijnlijke TKA – de zogenaamde 'onverklaarbare pijn' - is de zorg voor deze patiënten een grote uitdaging. Uit de literatuur blijkt dat factoren gekoppeld aan een pijnlijke knieprothese het vrouwelijk geslacht, een jongere leeftijd op het moment van de operatie en een hoger dan normale depressie- of angsttoestand omvatten. Vooral de Pain Catastrophizing Scale (PCS), lijkt de uitkomst van de patiënten na TKA significant te beïnvloeden. Toch mag deze psychologische verklaring geen dekmantel zijn om mechanische en biologische oorzaken weg te wuiven. Chirurgen dienen te begrijpen dat 'onverklaarbare' pijn niet betekent 'onbegrepen' pijn, maar meestal wel 'nog-niet begrepen' pijn. De doelstelling van deze thesis was te verklaren waarom sommige, blijkbaar goedgeïmplanteerde TKA, pijnlijk blijven, en de rol van de bot-implantaat mismatch en weke delen inklemming bij residuele pijn te onderzoeken. Onze hypothese was dat een kleine anatomische mismatch – een gebrek in het herstellen van de natuurlijke anatomie – op zijn minst een deel van deze residuele pijn kan verklaren.

Bij continu prospectief gevolgde patiënten met TKA hebben we aangetoond dat overmaatse componenten een erkende oorzaak zijn van residuele pijn. Metingen met een CT-scan toonden

een mediolaterale prothese overhang in ten minste één gebied bij 66% van de femora en bij 61% (mediolateraal) tot 87% (anteroposterieur) van de tibia's. De pre- naar postoperatieve verbeteringen van de pijn- en functiescores waren significant groter bij patiënten zonder overhang, in vergelijking met patiënten met overhang. *Regression en latent class analyse* toonde een significant negatieve correlatie tussen algemene overdimensionering en globale uitkomsten. Een dergelijk hoog percentage van bot-implantaat mismatch kan worden verklaard door menselijke anatomische variaties en de verschillende chirurgische technieken. Uit deze CT-scan database werd een gedetailleerde morfometrische analyse verricht op het niveau van de standaard TKA botsnede en natuurlijke bot parameters werden vergeleken met deze van TKA modellen. De invloed van de chirurgische techniek op de bot-implantaat mismatch werd ook onderzocht. (1) De morfologie van tibiale plateaus is afhankelijk van welke rotatie-as gekozen wordt. De keuze voor het afstemmen van de tibiale component met de posterieure tibiarand, de trans-epicondylaire as of de anterieure tuberositas tibia as dient het ontwerp van de component te beïnvloeden. Er moet ook enige variatie mogelijk zijn als chirurgen tegelijkertijd optimale prothetische dekking willen en afstemming met het extensiemechanisme. De studie benadrukt de grote variabiliteit in tibiaal plateau morfologie, met tot 17% van patiënten met een omgekeerde asymmetrie (lateraal deel groter dan mediaal) en illustreert dat aangepaste implantaten voordelig zouden kunnen zijn voor extreme gevallen van asymmetrie. (2) Met betrekking tot de morfologie van het distale femur, uit de nieuw gedefinieerde 'trapezoidicity' verhouding is gebleken dat een 'rechthoekig-trapeziumvormig' variabiliteit van het distale femur niet mag worden genegeerd. De meeste prothetische overhangen werden waargenomen bij trapeziumvormige femurs en de meest geteste femorale implantaten bleken uiterst rechthoekig te zijn in vergelijking met de beenderige contouren van het distale femur. (3) We hebben de afmetingen van de achterste condyli onderzocht en de invloed van externe rotatie van de femorale component bij potentiële prothetische overhang of bij onvoldoende dekking. Exorotatie versterkt de asymmetrie tussen de mediale en laterale condyl en verergert de prothetische overhang, met in het bijzonder de superolaterale zone.

Tenslotte werd een in-vitro beeldvormingsprotocol ontwikkeld om de interactie van de weke delen met de implantaten te evalueren. Deze techniek is bruikbaar over de volledige bewegingsboog met verschillende soorten prothesen. Met behulp van dit nieuw gedefinieerde protocol werden de pre- en postoperatieve posities van de popliteuspees vergeleken ten opzichte van volledige extensie tot diepe flexie bij normaal formaat, overmaatse en ondermaatse implantaten. Dit experiment toonde aan dat een normaal-formaat tibiaal component het traject van popliteuspees wijzigt, terwijl een ondermaatse tibiaal component meer fysiologische patronen handhaaft. De gegevens tonen ook aan dat het overdimensioneren van de tibiale component met toename van één grootte, de popliteuspees aanzienlijk verschuift gedurende de volledige boog van de beweging.

De bevindingen uit de reeks van studies gebruikt in deze thesis bevestigen het bestaan van aanzienlijke anatomische variaties in menselijk knieën die niet worden gecompenseerd door hedendaagse TKA ontwerpen. De resulterende prothetische overhang en/of onderdekking zijn een veelvoorkomende oorzaak van weke delen inklemming die verantwoordelijk is voor inferieure functie en residuele pijn. Chirurgen moeten oppassen voor de gevolgen van bot-implantaat mismatch om weke delen inklemming te voorkomen. Fabrikanten moeten de anatomische verschillen erkennen en zo het ontwerp van hun implantaten en instrumenten verbeteren om prothetische overhang te voorkomen, zonder afbreuk te doen aan de botdekking en implantaatfixatie.

Abbreviations

AP	AnteroPosterior middle of the tibial plateau
APD	AnteroPosterior Distance
APL	AnteroPosterior middle of the Lateral tibial plateau
AP_L	AnteroPosterior dimension at the Lateral condyle
APM	AnteroPosterior middle of the Medial tibial plateau
AP_M	AnteroPosterior dimension at the Medial condyle
ATT	Anterior Tibial Tuberosity
BDI	Beck Depression Inventory
BMI	Body Mass Index
CT	Computed Tomography
FTA	FemoroTibial Angle
ICLH	Imperial College London Hospital
ITB	IlioTibial Band
KOOS	Knee Injury & Osteoasthritis Outcome
LCL	Lateral Collateral Ligament
LCS	Low Contact Stress
MCL	Medial Collateral ligament
ML	Mediolateral
ML_A	MedioLateral dimension on the theoretical distal resection slice: Anterior region (75% of the 'average AP' dimension)
ML_C	MedioLateral dimension on the theoretical distal resection slice: Central region (50% of the 'average AP' dimension)
MLD	MedioLateral Distance
ML_P	MedioLateral dimension on the theoretical distal resection slice: Posterior region (10mm anterior to the posterior condylar margin)
MOD	Maximum Overlap Distance
MPF	Maximum Passive Flexion
MPQ	McGill Pain Questionnaire
MRI	Magnetic Resonance Imaging
mTFA	mechanical TibioFemoral Angle
OA	OsteoArthritis

PCS	Pain Catastrophizing Scale
PPI	Present Pain Intesity
PRI	Pain Rating Index
PROM	Patients Reported Outcome Measurements
PT	Patellar Tendon
PTM	Postero Tibial Margin
QT	Quadriceps Tendon
ROM	Range Of Motion
SD	Standard Deviation
SF-12	Short Form 12
SF-MPQ	Short Form McGill Pain Questionnaire
SF36-MH	Short Form 36 Mental Health scale
STAI	State-Trait Anxiety Index
STL	STereoLithography
TC	Total Condylar
TEA	TransEpicondylar Axis
TFA	TibioFemoral Angle
THA	Total Hip Arthroplasty
THR	Total Hip Replacement
TKA	Total Knee Arthroplasty
TKR	Total Knee Replacement
UKA	Unilateral Knee Arthroplasty
VAS	Visual Analog Scale
VIF	Variance Inflation Factor
WOMAC	Western Ontario and MacMaster score

Introduction

With 100 to 250 implantations per year and per 100.000 inhabitants in western countries[1], total knee arthroplasty (TKA) is now a 'mass-product', with a great acceptance from the surgical community and from the public. We can guess that a surgeon arriving from the 19th century to visit our actual operating rooms or offices would be fascinated by our capacity to treat severely damaged knees and by the confidence of our patients. On the other hand, the consequence of this 'mass-product' status is a low tolerance to failures and to inadequate -or perceived inadequate- outcomes. Therefore, despite more and more reliable techniques and technology, a significant proportion - up to 25% - of patients remain dissatisfied after TKA.

Surprisingly patient's satisfaction is quite a recent preoccupation in the field of knee arthroplasty. Historically, the priority for surgeons and engineers was to address mechanical challenges such as manufacturing processes, implant fixation and wear of bearing surfaces. Once these problems were partially solved, improvement of surgical techniques and instruments became the priority. While TKA widespread in the medical community the need for evaluation became obvious and many scoring scales were constructed, mostly based on 'objective measurements' such as range of motion, limb alignment and distance of walk. New tools based on patients' self-evaluation (perceived outcomes) appeared in the early 1980s[2] and thanks to these 'Patients Reported Outcome Measurements' (PROM) physicians focused on the subjective results and listen to the patients' voice.

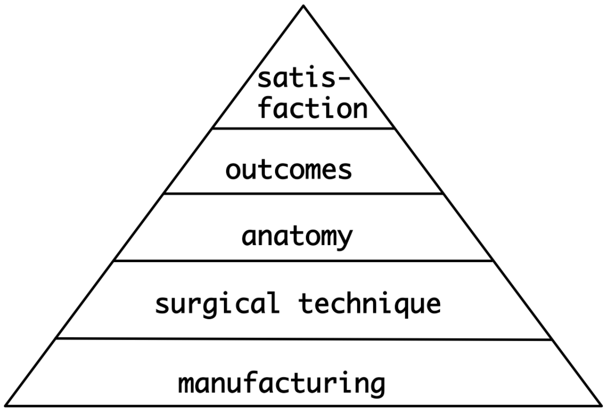

Figure 1: Like in the Abraham Maslow hierarchy of needs, physicians prioritized the safety of the manufacturing process, then the accuracy of the surgical technique and then improved designs. Sophisticated outcomes measurements tools were developed recently.

This paradigm shift modified our perception of outcomes[3, 4] and revealed that surgeons are more frequently satisfied than patients. Several investigators demonstrated in the last decade that patient satisfaction after TKA might differ from the objective outcomes: patient expectations and psychological factors are also major determinants in the subjective result[5].

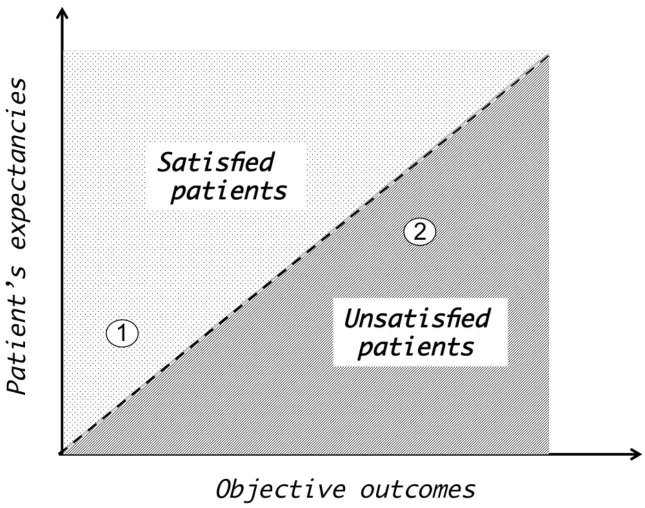

Figure 2: Patient's satisfaction after TKA depends not only on the quality of the objective result but also on patient's expectations. Patient 1 with a poor objective result is satisfied due to his low expectations, while patient 2 with a better objective result is dissatisfied.

However, even if psychological factors cannot be neglected in our medical decisions and in our evaluations, their importance should not be exaggerated and most residual pains after TKA are in fact due to mechanical problem. In the authors' experience, poor outcomes are often secondary to imperfect anatomic restoration, due to implant malposition, implant mal-sizing or to inadequate implants designs. Recognizing these poor conditions is one of the challenges when dealing with residual pain after TKA.

In our highly technological world, where sophisticated devices invade our daily life, the layman would be surprised to know how limited is the range of designs and sizes offered to surgeons during surgery to match human diversity. With the first knee arthroplasties, developed according to the nineteenth century concepts, joints were simply resurfaced with surrounding soft-tissues. This was the basic technique up to the mid-twentieth century, when surgeons, like Campbell and Smith Petersen began using metallic individualized implants. Due to the technological limitations, manufacturing and surgical techniques were unreliable and these procedures were indicated only in case of severe disability. Reliability and safety in the manufacturing process appeared with the 'modern TKA' when implants designs and sizes became 'carved in stone'.

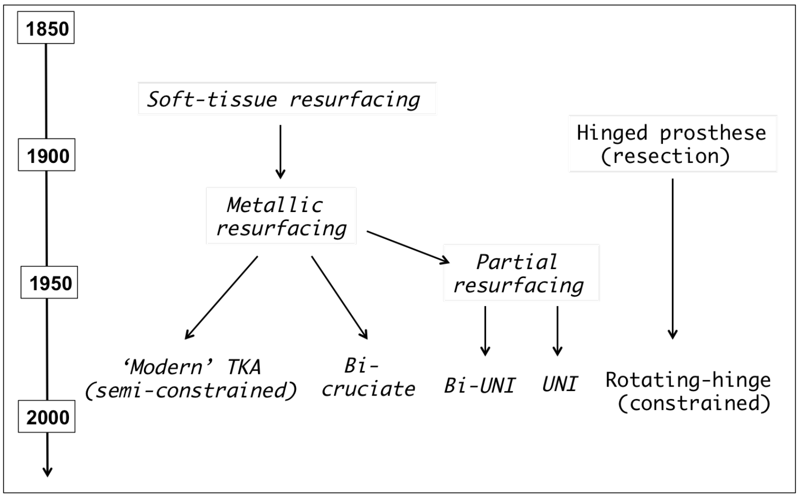

Figure 3: Up to the mid twentieth century, knee arthroplasty was a resurfacing procedure, using soft tissues. From 1940 Campbell and Smith-Petersen introduced customized metallic resurfacing. In the early 1970s' implant designers defined the design of the implants: the modern TKA was born. In parallel the branch of the hinged prostheses began in 1891 and partial implants started in the early 1950s'.

Pillars of 'modern' TKAs were then built in the 1970s' thanks to the progress of metallurgic process (molded chromium-cobalt) and of surgical techniques (universal instrumentations). However, reliability and safety in the whole process was obtained at the price of a limitation in the range of designs and sizes ap source of other difficulties.

The objective of this thesis was to investigate the causes of poor results after TKA with special interests to (i) bone-implant mismatch and (ii) soft tissue-implant impingements. The driving hypothesis of this work is that most apparently unexplained pains after TKA are due to a lack of anatomic restoration leading to soft tissue impingement. This phenomenon has never been investigated in the previous literature due to the difficulties to visualize in vivo the soft-tissue around TKA and to quantify precisely the bone-implant mismatch. Confirming or refuting this hypothesis could have clinical consequences concerning the optimal sizing and positioning of the prosthetic components and the evolution of implant design towards more soft tissue-friendly geometries.

This thesis comprises three main sections. The first section provides a brief historical overview and investigates whether current TKA meet patient expectations, particularly for sport and recreational activities, focusing on subjective results and patient satisfaction. A literature review of the role of psychological factors that influence subjective outcomes follows, with particular interest the rate of residual pain after surgery. Whether optimal bone-implants fit can be achieved with current TKA, and whether over- or under-sizing might influence outcomes will be investigated, in the two last chapters of this section.

The second section describes the anatomic variations of the bony contours at the knee joint in the human population and analyzes the influence of implant positioning and surgical technique on the shape of the bony contours. The ability to reproduce the shape of the native tibial plateau and femoral condyles with commercially available prostheses will be investigated using contemporary imaging technology.

The last section focuses on the forgotten dimension of the knee joint: the soft tissues and the knee envelope. It was hypothesized that residual pain in TKA could be due to impingements of the soft tissues against non-anatomic implants or against mal-positioned or mal-sized implants. A special focus was paid to the popliteus tendon, which is a high risk structure due to its unique intra-articular location.

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Section I

Do we reach our goals with current TKAs’

1. A historical perspective of TKAs

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A brief history of TKA

Contemporary total knee prostheses, as we know them nowadays, result from a long 'Darwinian evolution', by which only few concepts and designs survived. The first surgical techniques - described during the nineteenth century - intended to treat patients with severe knee disease in which joint surfaces had disappeared, mostly due to tuberculosis[1]. The principle was to resect and cover the damaged bone surfaces with soft tissue, mostly the ilio-tibial band (fascia-lata) or the joint-capsule, creating a 'resurfacing' of the knee. At that time, this soft-tissue interposition technique was commonly used to treat joint ankylosis, whatever the joint[2]. The first detailed descriptions of such 'excisions of the knee joint' were reported by William Fergusson in 1861[3] and by Peter Price[1], both London surgeons. In the early 1900s, surgeons tried to use other interposition tissues, such as fat tissues or pig bladder[4] but the fascia-lata remained the rule[5-7]. The surgical technique nicely detailed by Campbell, used the contralateral fascia-lata as a graft (Figure 1)[8, 9] with good long term reported outcomes, particularly on the pain[10].

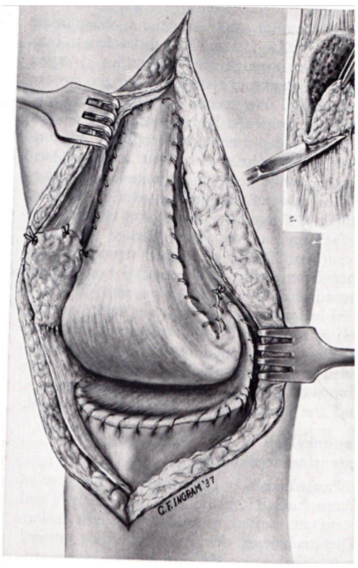

Figure 1: The knee arthroplasty as described by Campbell used the contralateral Fascia Lata.

From: Waring TL Arthroplasty In Campbell's operative orthopaedics. Crenshaw editor. The C.V. Mosby Company Saint Louis (MO) USA, 1963, p 1081.

Synthetic tissues have also been used such as cellophane by Samson in 1949[11], nylon by Kuhns in 1950[12], and vitallium, a chrome-cobalt alloy[9, 13-15]. In March 1940, Campbell reported four cases of knee replacements made with a molded plate of vitallium used to resurface the distal femur (Figure 2). In his article the technique was clearly described: *"…Prior to the operation, the size of the plate was estimated from roentenograms and constructed to fit over the anterior surface of the lower end of the affected femur. Since the anatomy of the knee joint precludes the interposition of metal without internal fixation, the plate was maintained in position by two posterior triangular flanges hooked into the surface of the condyles, and by one vitallium screw inserted into the anterior surface of the shaft of the femur…"*[15].

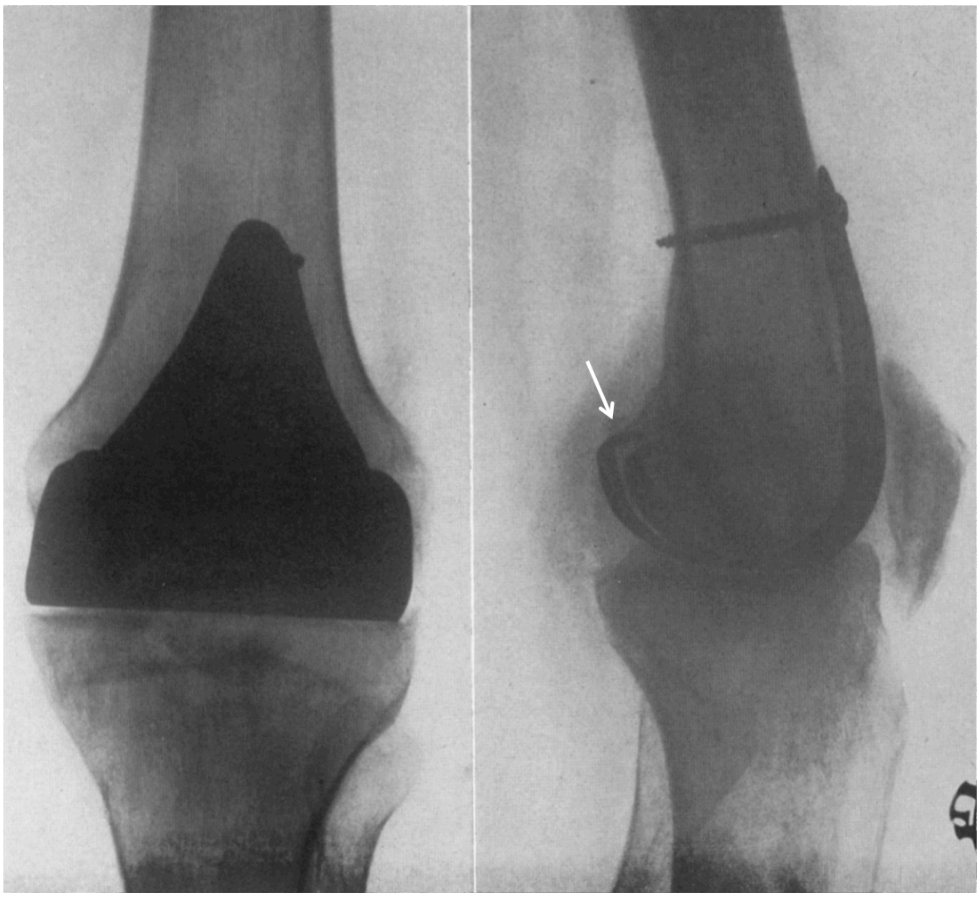

Figure 2: The vitallium knee arthroplasty of Cambell.

From Campbell W (1940) interposition of vitallium plates in arthroplasties of the knee. Am J Surg 47 (3):639-641. With permission

At that time the metallic interposition was considered as experimental and the author still recommended the use of fascia lata. The concept of resurfacing arthroplasty was then standardized by Smith-Petersen who implanted a femoral metal mold, customized in an ‘office laboratory’ requiring minimal bone resection of the distal femur while the tibia was left intact (Figure 3)[14, 16].

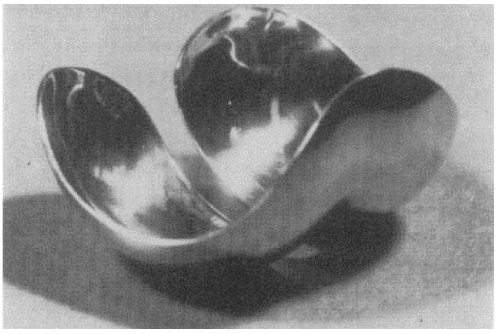

Figure 3: The Smith Petersen mould arthroplasty.

From Shetty A, Tindall,A. Ting, P. Heatley, F.W. (2003) The evolution of knee arthroplasty. Part I. Current Orthopaedics 17 :322-325. With permission

Due to some instabilities of the free metallic insert an intramedullary fixation was designed at that time by Smith-Petersen (Figure 4)[14].

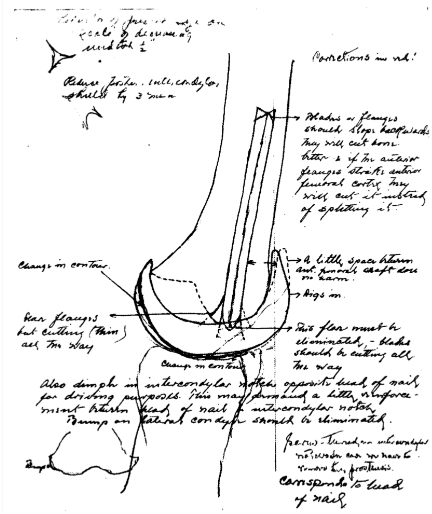

Figure 4: Drawing from Smith-Petersen. The mould femoral component has an intramedullary extension to improve component’s stability.

From Jones WN (1969) Mold arthroplasty of the knee joint. Clin Orthop Relat Res 66:82-89. With permission

During the same period the concept of hinged prostheses in which all the bone extremities were replaced by an artificial mechanics developed in Germany. The first hinged prosthesis, made of ivory, was designed and implanted by Themistocles Gluck in May 1890 in Berlin, on a 17 years old lady (Figure 5)[17, 18].

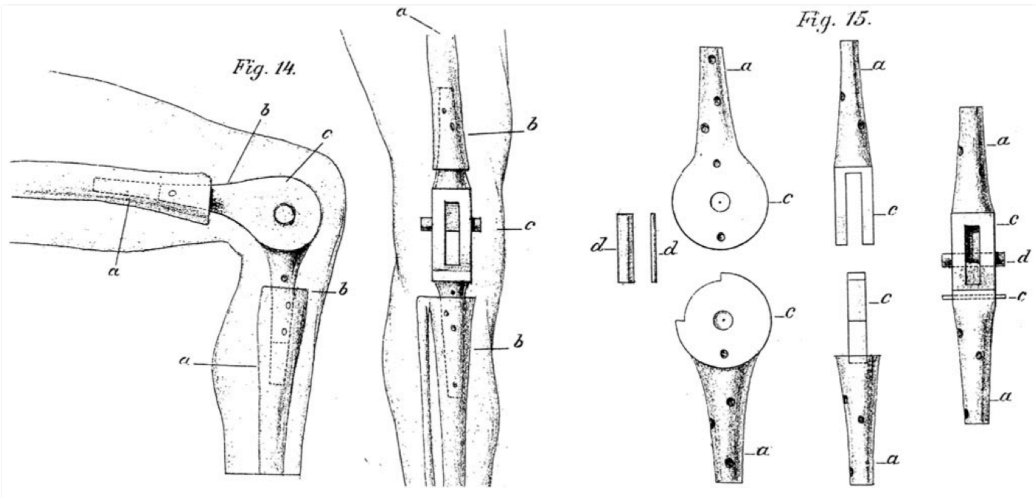

Figure 5: The first hinged prosthesis of Glück.

From: Brand RA, Mont MA, Manring MM (2011) Biographical sketch: Themistocles Gluck (1853-1942). Clin Orthop Relat Res 469 (6):1525-1527. With permission

The implant was fixed into the bone with a rudimentary cement made of 'copper amalgam, plaster of Paris, and a stone putty (made with pumice or gypsum)'[18]. The initial series included three patients suffering from tuberculosis but two implants had to be removed due to the progression of the infection. Following this early experience, the concept of hinged prosthesis was explored and developed in the 1950s by several authors like Merle d'Aubigné in 1953, Moeys in 1954, Seddon and Heinze in 1955. Walldius prosthesis developed in 1951 in Sweden was made with acrylic[19] and then changed to cobalt-chrome in 1958[19-22]. Several of these early constrained designs were still in use in the 1970s along with several other designs such as Shiers'[23] in the United Kingdom and the Guepar prosthesis in France[24, 25].

On the other side of the spectrum of the constraint, conservative partial implants appears also in the 1950s. The goal of these implants was to replace the damaged femoro-tibial articular surfaces, without sacrificing the cruciate ligaments. In the early1950s McKeever implanted the first unicompartmental free metallic insert, without any bone resection[26]. MacIntosh followed in 1954 and use uncemented inserts made successively of Acrylic, Teflon, Titanium and Vitallium[27]. These implants had a concave upper surface articulating with the condyle and a flat irregular lower surface requiring a tibial cut. Thereafter, numerous surgeons developed and improved the concept of unicompartmental prosthesis both in Europe and in North America[28-31].

In 1968, Frank Gunston, a Canadian orthopedic surgeon from Winnipeg, met John Charnley in Wrightington during a hip travelling fellowship. He had the idea of implanting cemented unicompartmental prostheses on both tibiofemoral compartments and designed the polycentric knee (Figure 6)[32]. The excessive constraint of these implants, related to the depth of the tibial components, lead to a high failure rate[33].

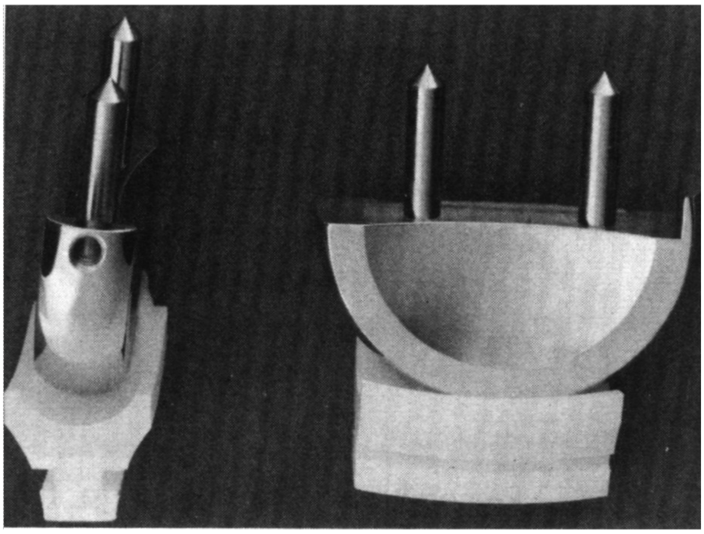

Figure 6: The Gunston prosthesis (Polycentric knee)

From Ranawat Anil S, Ranawat Amar S, Ranawat Chitranjan S The history of Total Knee Arthroplasty. In Bonnin M, Amendola N, Bellemans J, MacDonald S and Ménétrey J. The Knee Joint: surgical technique and strategy. Springer. Paris. 2012. P697-709. With permission

Chitranjan Ranawat, Allan Inglis, John Insall and Peter Walker continued this experience and designed in 1971 the Duocondylar prosthesis (Figure 7)[34]. As for Gunston's the two polyethylene tibial plateaus were independent, the cruciate ligaments were preserved and the patellofemoral joint was not concerned, but here both prosthetic condyles were integrated in a single metallic component.

Figure 7: The Duocondylar prosthesis

From Ranawat Anil S, Ranawat Amar S, Ranawat Chitranjan S The history of Total Knee Arthroplasty. In Bonnin M, Amendola N, Bellemans J, MacDonald S and Ménétrey J. The Knee Joint: surgical technique and strategy. Springer. Paris. 2012. P697-709. With permission

The contemporary TKA

The real modern total prostheses developed during the 1970s, firstly at the Imperial College in London Hospital (ICLH) by Michael Freeman and Swanson with the ICLH prosthesis (Figure 8)[35-37].

Figure 8: The ICLH prosthesis

From Ranawat Anil S, Ranawat Amar S, Ranawat Chitranjan S The history of Total Knee Arthroplasty. In Bonnin M, Amendola N, Bellemans J, MacDonald S and Ménétrey J. The Knee Joint: surgical technique and strategy. Springer. Paris. 2012. P697-709. With permission

Simultaneously, in the Hospital for Special surgery in New-York the inventors of the duocondylar improved their design by including the patellofemoral joint and developed in 1974 the Duopatella prosthesis, which is the predecessor of many actual cruciate retaining prostheses (Figure 9)[38].

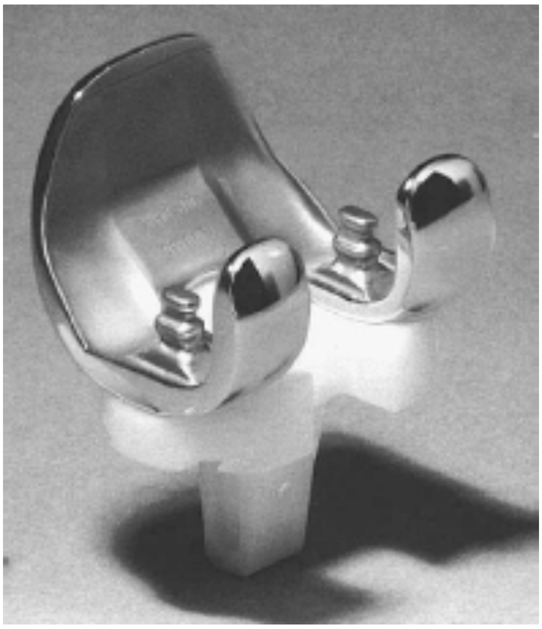

Figure 9: The Duopatella prosthesis

From Ranawat Anil S, Ranawat Amar S, Ranawat Chitranjan S The history of Total Knee Arthroplasty. In Bonnin M, Amendola N, Bellemans J, MacDonald S and Ménétrey J. The Knee Joint: surgical technique and strategy. Springer. Paris. 2012. P697-709. With permission

The Total condylar (TC) developed in 1974 by the same team in New York became the first real widely used modern TKA[38-40]. All condylar surfaces and the patello-femoral joint were replaced with a round-on-round geometry of the bearing surfaces, with better stability. However, the sacrifice of the posterior cruciate ligament was source of posterior-tibial translation in flexion and limitation in the range of motion. To solve this problem, the first posterostabilized TKA, the Insall-Burstein prosthesis, was developed in 1978[41, 42].

Several other significant evolutions occurred also during the 1970s: (i) metal-backed tibial implants introduced the concept of modularity[43]. (ii) uncemented prosthesis appeared in the early 1970s with the Yamamoto's prosthesis, whose components were stabilized by fins and staples[44]. (iii) the porous coated uncemented knee developed in 1978 by Hungerford, Kenna and later Krackow was the first knee prosthesis with a sophisticated coating aiming at improving osteointegration[45, 46]. (iv) mobile-bearing implants were introduced by Goodfellow and O'Connor in 1976 for unicompartmental replacements[31] and at the same time Buechel and Pappas developed the Low Contact Stress (LCS) rotating TKA, introducing the concept of conformity[47, 48].

In the early 1980s the pillars of the modern TKA were therefore built with all the great concepts: posterostabilisation and posterior cruciate conservation, fixed- and mobile-bearing, conforming and non-conforming polyethylene, ligament balancing and measured resection techniques, universal instrumentation and modularity. Standardized manufacturing process provided great improvements concerning bone fixation, resistance to wear and surgical reliability thanks to the instrumentation.

The limits of contemporary TKA

Even if the 'pre-modern' TKA appears to be conceptually a resurfacing procedure, the 'contemporary' TKA diverges from this concept. The design of the components, drawn in the 1970s - with a partial knowledge of knee anatomy - does not strictly reproduce the highly variable contours of the native knee. The positioning of non-anatomic implants in the non-deformable knee envelope may generate ligament imbalance and impingements, source of residual pain. Therefore, while implanting a TKA, surgeons still have to compromise between optimizing implant-bone fit, rotational alignment, coronal alignment and tibia-femur mismatch. As a result, sizing of implants is frequently challenging and femoral oversizing have been reported in 76% of the patients[49]. Several technical modifications aimed at solving partly these difficulties, but there is still no consensus between anatomic versus kinematic alignment, gap balancing versus measured resection technique and concerning the kinematics, each option having advantages and disadvantages. While the soft-tissue balancing and aligment strategies (mechanical, anatomic or kinematic) extend beyond the scope of this thesis, it is worth noting that their intended benefits can often induce drawbacks due to prothetic overhang and/or bone undercoverage.

Despite great improvements that occured in the last decade, historically the design and the range of sizes have always been limited in TKA due to industrial constraints and partial anatomical/biomechanical knowledge.The manufacturing of chromium-cobalt implants is a complex process due to the hardness of the alloy and historically, machining was hardly usable. The process was traditionally based on molding technology, which explains the reluctance of manufacturers to develop an excessively expensive range of sizes. In example, during the first decade of the Total Condylar only one femoral size was available[40].

While the anatomy of the knee joint was well described before the 1970s, the extent of anatomic variations in human populations was vastly underestimated, because most studies were with a limited number of specimens[50]. From the 1990s, CT scan based morphometric analysis become possible with series of hundreds of subjects[51]. In the 2000s, MRI or CT scans from large populations provided series reaching a thousand people[52]. More recently, databases used for patient-specific instrumentation, gave access to several thousands of scans, coming from different continents[53]. Thanks to these new data, we now understand the great variability of knee anatomy in humankind. Initially designed in western countries for western populations, TKA is now a worldwide procedure, and therefore addresses several populations whose anatomy differs from the original populations. Particularly the use of TKA in Asian populations revealed differences in the shape of the distal femur[54] and proximal tibia[55].

In the 1980s and 1990s the range of sizes of TKA increased in a proportional way from the original designs, assuming that the shape of the knee was strictly identical among populations and patients sizes (Figure 10).

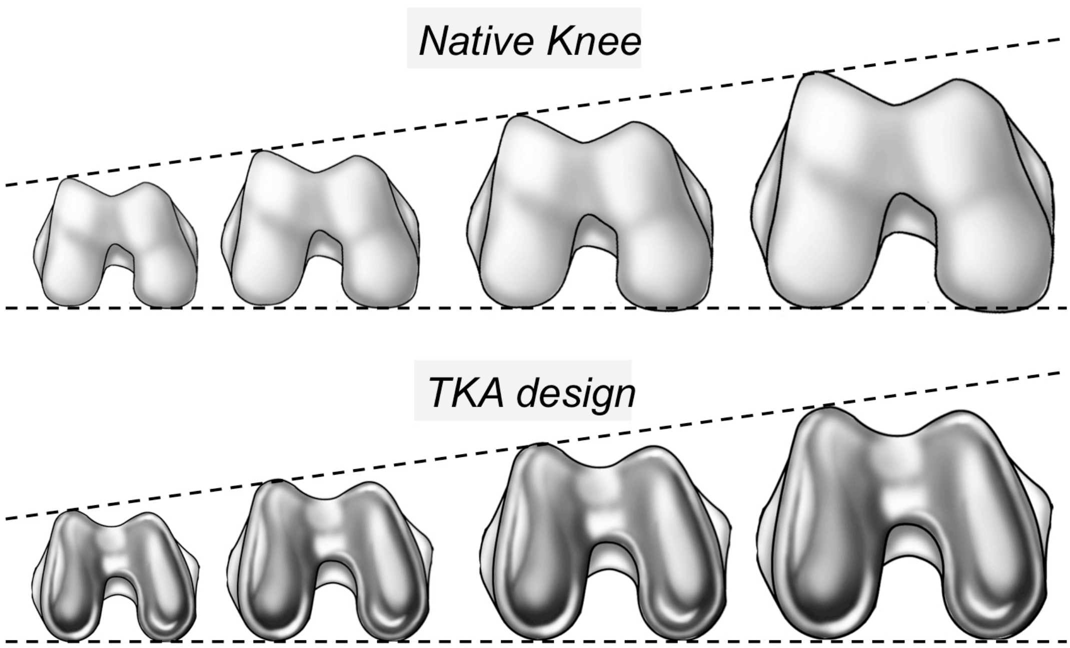

Figure 10: In the 80s and 90s the extension of the range of size was proportional, assuming that the shape of the knees was identical, whatever patient's size gender, morphotype of ethnicity.

It is only in 2003 that Hitt et al[56] introduced the concept of 'aspect-ratio' in the orthopaedic community and demonstrated, followed by other researchers, that the shape of the distal femur and proximal tibia is largely variable in the human population, depending on gender, ethnicity, morphotype and size[52, 57-59]. Following these findings, several manufacturers developed additional 'narrow versions' in their range of femurs, also known as 'gender knees'[58, 60-62].

In the last decades surgical techniques evolved, in particular the orientation of components, without adequate enhancements of implant design. In the early times, most textbooks taught to align the femoral component with the posterior condylar line[46, 63, 64] but it has now been demonstrated that external rotation improved patello-femoral tracking[65, 66] and ligament balancing[67-69]. Therefore most instrumentation introduced some degrees of femoral external rotation, which modifies the dimensions of the resected posterior condyles, and subsequently induces mismatch with the implants[70]. The Posterior Tibial Margin was also the historical reference axis for rotation of the tibial component[64, 71, 72] but it has been proven that it may induce internal malrotation, and thereby cause patellar pain and instability[50, 51, 66, 73]. Therefore a more external rotation of the tibial component is now accepted but it also modifies the bone-implant fit[74].

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2. Functional outcomes: Can patients really do sport after TKA?

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Abstract

Function and sport participation was analyzed via a self-administered questionnaire in 347 patients with unilateral non complicated TKA. It was 227 women and 120 men with a mean age of 75years (range, 28 to 94) and a mean follow-up of 44 months (range, 13 to 71). 237 patients (68%) reported that their knee was "normal", 56% that their activities were limited by their knee, and 66% that they were as active as they expected to be before the intervention. Of them, 98% were satisfied. Of the patients who were insufficiently active, 52% were not satisfied with their outcome ($p<0.0001$). Neither the duration of preoperative pain, the age at evaluation or the number of previous surgeries influenced the subjective result or the degree of patient satisfaction. Among patients under 75 years, 10% regularly participated in strenuous sports but only 13% felt that this ability was important. When participation was analyzed in the motivated patients subgroup, 63% regularly took part in at least one impact sport.

Introduction

In only a few decades, total knee arthroplasty (TKA) has come to be a reliable intervention that can eliminate pain and improve quality of life in patients suffering from degenerative disease of the knee[1]. The number of prostheses implanted every year has progressed substantially, thus improving both implant design and implantation technique. Simultaneously, patients' functional demand and expectations have evolved, with many now wishing to resume recreational activities or sports after their knee surgery[2, 3]. Yet Noble et al.[4] has reported that satisfaction of preoperative expectations significantly conditions the subjective result, which is not always correlated with the objective result[5, 6]. It is therefore important to know precisely how the knee will evolve functionally after TKA so that the patient can be informed and not develop unrealistic expectations.

Sports activity after TKA has been studied from several different perspectives: some authors have analyzed this within selected populations of athletes[7-10]; others have studied the risks related to sports activity[11-14]; still others have attempted to standardize the recommendations to be given to patients with prostheses[11, 15] Bradbury et al.[16], Weiss et al.[17] and Dahm et al.[18] analyzed participation in sports in a nonselected population of patients who had undergone TKA. In addition, Noble et al.[19] showed that sports participation and motivation in a control population of the same age with a normal knee was limited because of the consequences of aging. Iorio et al.[20] and Lingard et al.[21] demonstrated that the final result and activity depended on patient motivation. It is therefore important to analyze sports participation not only in the overall population, but also in the population of motivated patients who wish to resume sports activities, and analyze the reasons for nonparticipation.

Our hypothesis was that sport participation after TKA is not only dependent of the TKA itself but also from the motivation of the patient.

The objectives of this study were to analyze, within a nonselected population of TKA patients: (1) patient participation in functional and sports activities, (2) the correlation between the functional result and patient expectations in terms of daily living and recreational activities, and finally (3) the ability of motivated patients to resume demanding activities after TKA.

Material and methods

A sequential series of 670 patients undergoing TKA between January 2003 and December 2004 in four centers was included in this study. Patients who's contralateral knee had been operated on for TKA, previously (30 patients) or since the inclusion period (54 patients), were excluded from the study. 49 more patients were dead or had changed address. A self-administered functional assessment questionnaire was sent to each of the 544 remaining patients. The patients who had not returned the questionnaire or who had returned an incomplete questionnaire after two mailings were removed from the study.

A total of 347 patients participate in the study (Table 1). All operations had been performed with a posterostabilized TKA, with the patella resurfaced in 308 patients and with a mobile bearing in 282 cases. The tibia was cemented in 338 cases and the femur was cemented in 337 cases. A total of 247 Noetos implants (Tornier, Montbonnot, France) and 100 NexGen implants (Zimmer, Warsaw, IN, USA) were used.

Table 1: Patient demographics

	n = 347	
Age (years)	74.8	(28.0 - 94.0)
Women : Men	227 : 120	
Follow-up (months)	44.0	(13.0 - 71.0)
BMI (kg/m^2)	27.9 ± 4.9	(17.0 - 46.0)
Other joints (Charnley group)		
A	178 (51%)	
B	100 (29%)	
C	69 (20%)	
Indication for TKA		
Osteoarthritis	331 (95%)	
Rheumatoid arthritis	9 (3%)	
Spontaneous necrosis of medial condyle	7 (2%)	
Localization of the lesions		
Medial compartment	151 (44%)	
Lateral compartment	48 (14%)	
Patellofemoral	4 (1%)	
Three compartments	144 (41%)	
Previous surgery (including arthroscopy)		
0	278 (80%)	
1	45 (13%)	
2	15 (4%)	
≥ 3	9 (3%)	
Duration of preoperative pain		
> 10 years	78 (22%)	
5 to 10 years	118 (34%)	
2 to 5 years	83 (24%)	
1 to 2 years	47 (14%)	
< 1 year	4 (1%)	
do not remember	22 (6%)	
Medical limitation for functional assessment	50 (14%)	
SF12 V2 score (norm-based)		
Physical score	49.5 ± 10.6	
Mental score	1.7 ± 1.9	

The questionnaire was anonymous and the patients never wrote their names on the document they completed. After the questionnaire was returned, the data were captured by an independent company (Clininfo, Lyon, France) and the data were analyzed by the Biostatistics Department of the Hospices Civils de Lyon (Lyon, France).

The first part of the questionnaire analyzed global health status with the SF12 V2 score[22] and also comprised five questions measuring overall patient satisfaction with their operation. The second part comprised questions on the activities of daily life used to calculate the WOMAC® score[23] with its three subscores: pain (five questions), stiffness (two questions), and physical function (17 questions corresponding to 17 activities of daily life). Each of the subscores was transformed to a scale ranging from 0 (best result) to 10 (worst result). An overall score on a scale from 0 to 10 was calculated based on the mean of the three subscores per patient.

The third part analyzed sports participation, which was studied using the methodology and functional score described by Weiss et al.[17] (Appendix). Participation in sports was analyzed more specifically in the group of patients aged less than 75 years at the time of evaluation. This subgroup included 141 TKA patients with a mean age at evaluation of 66.4 years (range, 28 to 74). For each activity, the patients were considered to participate in this sport if the question "How often do you do this sport?" was answered with "regularly but not often," "regularly and often," or "intensively." The nonparticipating subjects were those answering "rarely," "occasionally," or "never do this sport." The patients were considered motivated for an activity if the question "Is this activity important in your life?" was answered with "important" or "very important." The nonmotivated patients were those who responded "not important," "minimally important," or "moderately important."

Sports were grouped into light sports (stationary cycling, cycling, stretching, swimming, and golf), intermediate sports (gardening, hiking, gymnastics, strength exercising, sailing, and dancing) and strenuous sports (cross-country skiing, downhill skiing, tennis/squash, and running more than 500 m). A patient was considered to be motivated by an activity category if he or she responded "important" or "very important" to at least one of the activities in the category and was considered nonmotivated by an activity category if he or she responded “not important,” “minimally important,” or “moderately important” to all of the activities in the category. A patient was considered to be participating in an activity category if he or she regularly participated in at least one of the activities in the category and nonparticipating if he or she did not participate in any of the activities of the category.

Statistical analysis

Based on an a priori hypothesis, measures of the dependence between categorical variables (responses to the satisfaction questions) were tested using a Chi 2 test (or the Fisher exact score if the sample was too small). For the continuous data, a Student *t*-test was used to compare the means if two groups were compared and an ANOVA for more than two groups. For multiple comparisons, the signification threshold was lowered (Bonferroni correction). If the data was not normally distributed and if the sample was too small, a rank test was used (Kruskal-Wallis if there were more than two groups and the Mann-Whitney test for two groups). A test was statistically significant if $p<0.05$. All the statistical analyses were done with the Stata 10 software (StataCorp. 2007. Stata Statistical software: Release 10. College Station, TX: StataCorp LP).

Results

A total of 168 of the 347 patients (48.4%) were very satisfied with the TKA procedure, 120 were satisfied (34.6%), 38 were moderately satisfied (11%), 13 were somewhat dissatisfied (3.7%), and four were dissatisfied (1%). Four patients did not respond to this question. Of the responders, 144 patients (41.5%) were more active than before the intervention, 101 (29%) maintained the same activity level, and 93 (26.8%) reported they were less active than before the surgery (nine patients did not answer this question). 237 patients (68.3%) reported that their knee was normal for their age, and 108 (31%) said they could run if necessary (31%).

A total of 228 patients (65.7%) reported that they were as active as they expected to be before the intervention and 196 (56.5%) considered that their activities were limited by their knee (ten patients did not answer this question). Of the patients who reported that they were as active as they expected to be before the procedure, 98.2% were satisfied or very satisfied. Of the patients who reported they were insufficiently active, 52.3% were not satisfied ($p<0.0001$).

The duration of preoperative pain did not influence the subjective result (86.2% of patients satisfied or very satisfied when pain had lasted more than 5 years and 81.1% when it had lasted less than 5 years; $p=0.21$) or satisfaction of the preoperative expectations (71.9% of patients who had experienced pain for more than 5 years reported they were as active as they expected to be before the surgery versus 63.9% of them experiencing pain for less than 5 years; $p=0.13$). The age of the respondent did not influence the subjective result (82.8% satisfied and very satisfied in the over 75-year-olds and 85.7% in the under 75-year-olds; $p=0.46$). Fulfillment of preoperative expectations was independent of the number of surgeries on the knee: 79% of the patients who were as active as they wished to be had no previous surgery versus 75% of those who were not ($p=0.65$).

WOMAC and SF12 scores are detailed in table 2. A significant relation was found between patient satisfaction and the three components of the WOMAC score. Similarly, the three WOMAC subscores were better in patients who achieved their expectations with regard to activity (physical score, 1.0 if as active as expected and 3.7 if not as active as expected; pain score, 0.5 versus 2.0; stiffness score, 1.25 versus 2.5) (p<0.0001 for each test). The mean overall score was 1.8±1.8 in patients who had undergone patellar resurfacing and 1.7±1.8 in patients with a non-resurfaced patella.

Table 2: WOMAC and SF12 scores in the global series and in the group of patients under 75 years of age at surgery

	All patients (n=347)		Patients ≤ 75 yrs (n=141)		*p values* [1]	Satisfied (n=???)		Dissatisfied (n=???)		*p values* [2]
WOMAC										
Global score	1.7 ± 1.8	(0.0 - 9.0)	1.8 ± 1.8	(0.0 - 9.0)	*<0.05*	1.1 ?	(0.0 - 7.0)	4.2 ?	(0.0 - 9.0)	*<0.0001*
Physical function score	2.2 ± 2.0	(0.0 - 9.0)	2.0 ± 1.9	(0.0 - 9.0)	*<0.05*	1.2 ?	(0.0 - 7.0)	4.6 ?	(0.0 - 9.0)	*<0.0001*
Pain score	1.4 ± 1.7	(0.0 - 8.0)	1.5 ± 1.7	(0.0 - 8.0)	*<0.05*	1.0 ?	(0.0 - 7.0)	3.0 ?	(0.0 - 8.0)	*<0.0001*
Stiffness score	2.1 ± 2.2	(0.0 - 10.0)	2.0 ± 2.1	(0.0 - 10.0)	*<0.05*	1.2 ?	(0.0 - 7.0)	5.0 ?	(0.0 - 10.0)	*<0.0001*
SF12 V2										
Physical score	49.5 ± 10.6	(14.0 - 71.0)	50.3 ± 9.3	(19.0 - 67.0)	*<0.05*					
Mental score	41.4 ± 10.0	(13.0 - 61.0)	41.2 ± 10.6	(13.0 - 59.0)	*<0.05*					

[1] Between global series and patients ≤ 75 years at surgery
[2] Between satisfied and dissatisfied patients

Participation in sports and motivation for sports activities in the overall population was limited (Figure 1).

In the patients under 75 years of age, sports participation was more frequent, with 56% of the patients regularly participating in one or several activities in the light sports group, 66% in one or several activities in the intermediate group, and 10% in one or several of the strenuous sports group. However, patients' motivation for sports activities remained limited (Figure 1). A strong correlation was observed between participation and motivation (r=0.971, p=0.000) (Figure 2).

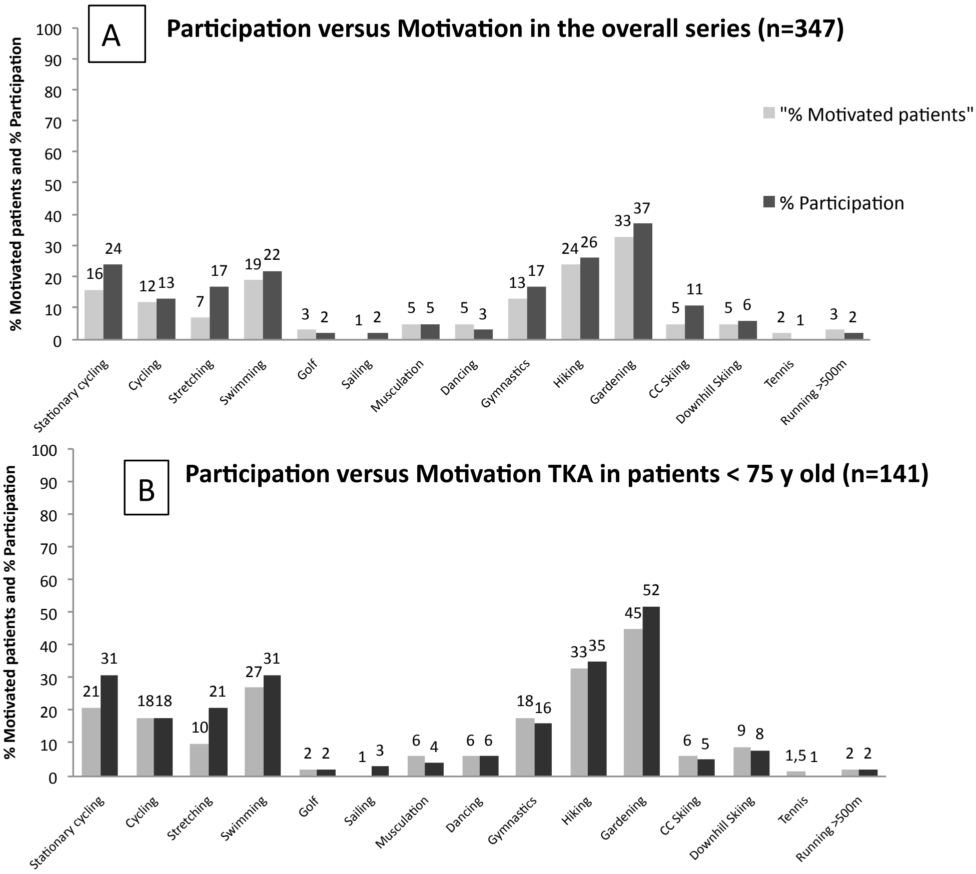

Figure 1: For each activity, the percentage of patients who participate regularly or intensively is represented in the dark grey column and the percentage of motivated patients in the light grey column. Results are presented (A) for the overall series and (B) for the subgroup of patients less than 75 years old. A patient was considered motivated for an activity if the answer to the question "Is this activity important in your life?" was "important" or "very important".

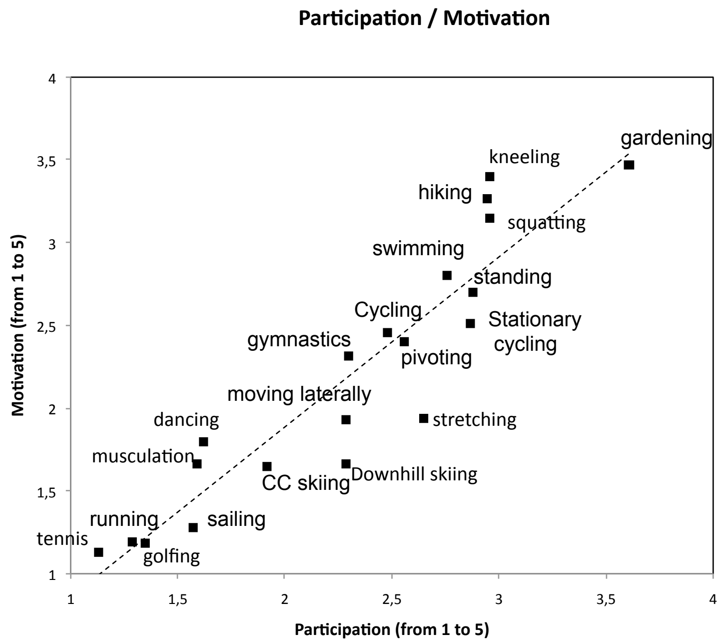

Figure 2: This graph represents the relation between motivation and participation for each activity in patients less than 75 years of age. The x-axis represents the mean participation score for each activity from 1 (rare) to 5 (intensive). The y-axis represents the mean motivation score for each activity from 1 (not important for me) to 5 (very important for me).

When participation in sports was analyzed in the motivated patient subgroup, participation was greater (Figure 3). Frequency of participation was also high in this group of motivated patients. Consequently, out of the 12 patients who downhill skied, 11 did so regularly or intensively; of the eight who cross-country skied, seven did so frequently or intensively; and the three who ran did so intensively (Table 3). Inversely, the absence of sports activity was rarely blamed on the operated knee (Figure 4).

Table 3: Frequence of participation and level of difficulty during practice

Activity	number	Level of participation		Level of difficulty during practice	
Stationary cycling	26	4.0 ± 0.8	(2.0 - 5.0)	1.7 ± 0.7	(1.0 - 1.0)
Cycling	22	3.7 ± 1.2	(1.0 - 5.0)	1.7 ± 0.6	(1.0 - 3.0)
Stretching	12	4.2 ± 0.6	(3.0 - 5.0)	1.8 ± 0.8	(1.0 - 4.0)
Swimming	37	3.7 ± 1.3	(1.0 - 5.0)	1.8 ± 1.0	(1.0 - 5.0)
Golf	3	4.3 ± 1.1	(3.0 - 5.0)	2.0 ± 1.0	(1.0 - 3.0)
Sailing	2	5.0 ± 0.0	(5.0 - 5.0)	2.8 ± 0.5	(2.0 - 3.0)
Musculation	5	2.6 ± 1.8	(1.0 - 5.0)	2.4 ± 0.5	(2.0 - 5.0)
Dancing	7	2.4 ± 1.9	(1.0 - 5.0)	2.1 ± 1.1	(1.0 - 5.0)
Gymnastics	21	3.8 ± 1.2	(2.0 - 5.0)	2.2 ± 0.6	(1.0 - 3.0)
Hiking	43	4.0 ± 1.0	(2.0 - 5.0)	2.1 ± 0.8	(1.0 - 4.0)
Gardening	56	4.3 ± 0.9	(1.0 - 5.0)	2.5 ± 1.0	(1.0 - 5.0)
Cross Country Skiing	8	2.9 ± 1.6	(1.0 - 5.0)	2.4 ± 1.4	(1.0 - 5.0)
Down Hill Skiing	12	3.5 ± 1.7	(1.0 - 5.0)	2.6 ± 1.0	(1.0 - 5.0)
Tennis	1	5.0 -	-	5.0 -	-
Running >500m	3	4.5 ± 0.7	(4.0 - 5.0)	3.7 ± 1.2	(3.0 - 5.0)

This table analyzes the group of patients <75 years old and motivated for each activity. For each activity, the level of participation and the level of difficulty attributable to the knee are mentioned on a 1-to-5 scale. (1 = no participation to 5 = intense participation; 1 = no difficulty to 5 = severe difficulty).

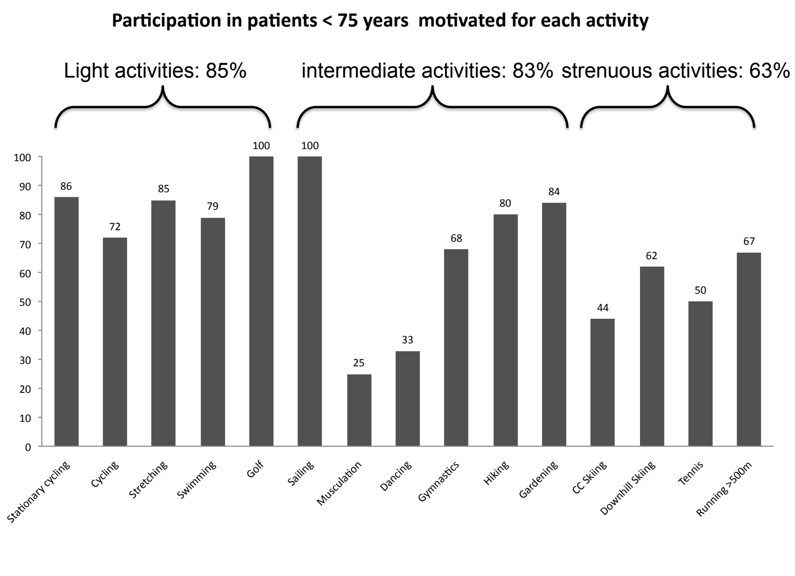

Figure 3: This histogram shows the percentage of regular or intensive participation for each activity in patients motivated for this activity. Participation in the three categories of sports is also shown, i.e., 63% of the patients motivated for one or more strenuous activities participate in one or more activities from this category on a regular basis.

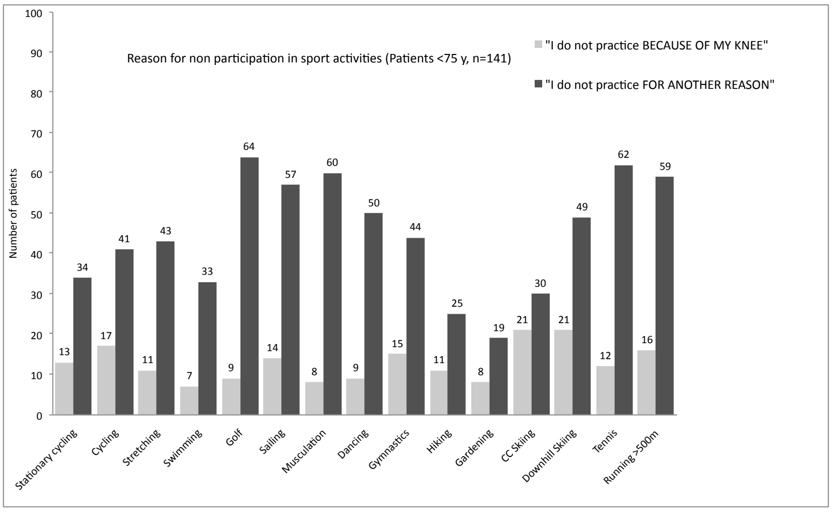

Figure 4: For each activity, this histogram shows the reason for nonparticipation (patients who answered *"I do not participate."*). Nonparticipation is attributable to reasons unrelated to the operated knee (dark grey) or caused by the operated knee (light grey).

Few patients indicated severe or very severe discomfort in their knee when participating in their activities (Table 3) and the relationship between frequency of participation in activities and knee symptoms was not significant ($r=-0.143$, $p=0.547$) (Figure 5).

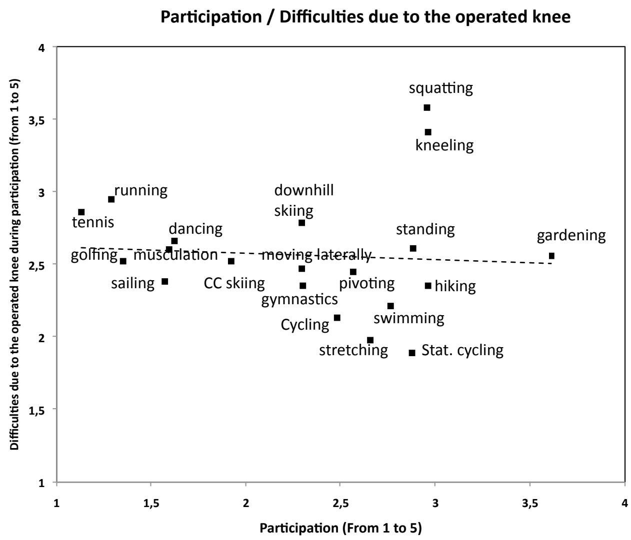

Figure 5: This graph represents the relation between participation/and difficulties for each activity in patients less than 75 years of age. X-axis represents the mean participation score for each activity from 1 (rare) to 5 (intensive). Y-axis represents the mean level of difficulty attributable to the knee during each activity from 1 (no difficulty) to 5 (severe difficulty).

The Weiss score for the overall series was 5.48 ±1.18. It was 5.8 for light activities, 5.49 for intermediate activities, and 5.1 for strenuous activities. The mean score for patients less than 75 years of age was 5.48±1.02. It was 5.92 for light activities, 5.51 for intermediate activities, and 5.06 for strenuous activities (Figure 6).

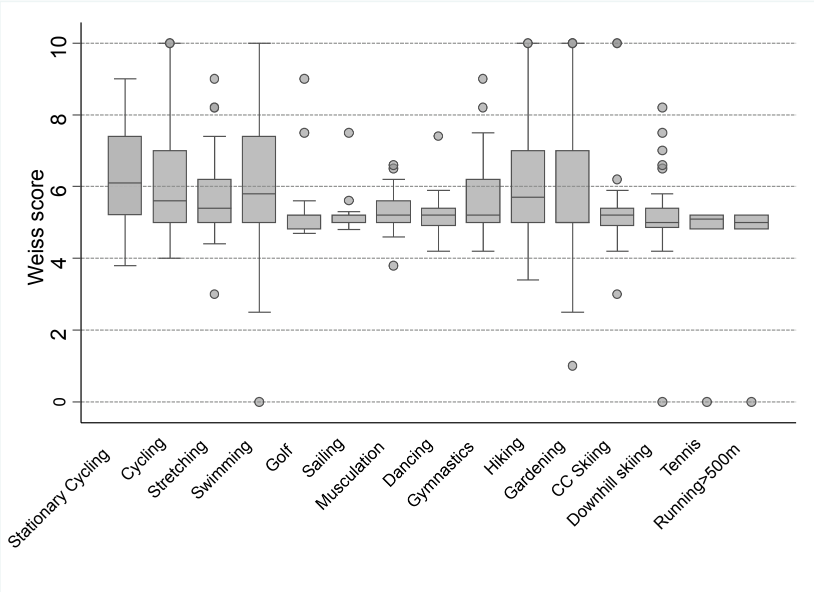

Figure 6: This graph illustrates the Weiss and Noble score from 0 (worse) to 10 (best) for each activity.

Discussion

The most important findings of the present study were that satisfaction of the patient's preoperative expectations was the main criterion conditioning the subjective result in TKA and that motivated patients were able to participate regularly in strenuous sport activities.

The strength of this study is that it specifically analyzes sports participation in subgroups of motivated patients, which considerably changes the results. Although only 10% of the all patients regularly participated in strenuous sports, this rate was 63% in the subgroup of motivated patients.

This study has several limitations. First, it was a retrospective investigation and the patients had received recommendations from their surgeon. Second, the study's evaluation does not take into account the patients' sports level. Finally, our response rate was only 64%. Our response rate (64%) could have been improved if the questionnaires had been followed up with telephone interviews, but this could have influenced the patients' responses.

The satisfaction rate after TKA reported in the literature varies from 50% to 91% depending on the criteriae of evaluation[6, 18]. Wright et al.[6] noted that although 75% of patients said they were globally very satisfied, only 55% report the same thing in term of return to activities of daily living and 50% for recreational activities. Similarly, it has been noted that only 68% of the patients after TKA had a satisfaction score superior to 80% when evaluated with VAS, from 0 (totally dissatisfied) to 100 (totally satisfied)[5].

The ability to resume sports and recreational activities after TKA motivates an increasing number of patients to undertake arthroplasty with confidence[3, 10]. To avoid unrealistic expectations, it is important to precisely analyze each patient's wishes and expectations and also to know the actual sports habits after TKA so that they can be properly informed.

The intention of the present study was to investigate the ability of motivated patients to resume demanding activities after TKA. It was not our intention to analyze the impact of participation in sports activities on the durability of TKA, but to provide an objective assessment of the actual sports activity in a nonselected patient population.

Several authors have shown that selected patients could resume strenuous sports activity after TKA. Mont et al.[10] reported a series of TKAs in former tennis players who were operated on at a mean age of 57 years. At 7 years of follow-up, all these patients played competitive tennis at least three times a week, with pain reported in only 12%. Mallon and Callaghan[8] report a series of TKAs in competitive golfers operated on at a mean age of 65 years. All had resumed golf a mean 18 weeks after surgery and played 3.7 times a week; 36% complained of pain after playing and only 16% while playing. Diduch et al.[7] analyzed sports participation in a population of 103 young TKA patients (mean age, 51 years) seen after 8 years. The mean Tegner score at that time was 3.5 (range, 1 to 6) and 19 had a score greater than or equal to 5. For Bradbury et al.[16], 65% of the patients who did sports resumed their activities after the intervention (20% for tennis). Chatterji et al.[24] report that 85% of the patients in a series of 144 TKAs took part in at least one recreational activity and after 1 year of follow-up, 75% participated in sports activities.

Sports activity in nonselected populations of patients with TKA has not been widely studied. Weiss et al.[17] compared sports activity in 176 patients who had a knee implant and 257 age- and sex-matched control patients. Dahm et al.[18] analyzed sports activity in a series of 1226 patients. The sports participation in these two studies was relatively close to our findings if certain cultural differences (golf) or regional differences (skiing) are excluded (Table 4). These two studies were also based on questionnaires sent to patients by mail with a response rate of 48% and 74%, respectively.

The notion of a good result in terms of sport participation after TKA is complex because three parameters come into play: actual participation, motivation for sports, and discomfort or pain during sports activities. Participation in sport activities depends on patient motivation, which conditions the level of discomfort and pain that they tolerate to be able to engage in their favorite activity. A very strong correlation has been observed between the level of activity desired by the patient before surgery and the final level of activity[20]. Our results confirm that a good result for TKA is not systematically a "pain free" or "symptom free" knee but a knee that satisfies patient's preoperative expectancies or main preoperative goals[25-27].

Weiss et al.[17] proposed an activity score integrating three parameters, motivation, participation and difficulties or pain during participation. However, this score's use of pain during an activity is weighted heavily in the negative direction, sharply decreasing the score. In addition, the calculation of the final score does not take the type of sport into account and weights strenuous sports and light sports identically. The results reported by Weiss et al. (5.7±1.6) were better than ours and varied by age group, with the best score observed in patients under 65 years of age (6.0±2), then in patients over 75 years of age (5.9±1.3), and finally in patients between 65 and 75 (5.4±1.2). The score in the control group reported by Noble et al.[19] was significantly higher than the score in the TKA population (6.9±0.3; $p<0.00001$).

The UCLA score[12] does not take into account the type of sport and does not include either motivation or discomfort and pain. In a series of 1026 patients, Dahm et al.[18] found a mean score of 7.1 (range, 1 to 10), which corresponds to regular cycling. The frequency of strenuous sports participation is close to that observed in our study (Table 4) and varies with patient age. Bauman et al.[28] report a mean score of 6.0 (range, 3 to 8) in a series of 184 TKAs: 29.3% were at level 7, corresponding to cycling, 23.4 were level 8, corresponding to golf or bowling. None of the patients was at level 9 or 10, corresponding to impact sports, skiing, or hiking with a backpack.

Table 4: Participation in sport activity in our study compared with the literature

	This study			Dahm 2008	Weiss 2004	Control group Noble 2005
	Global series	*Patients <75 yrs*	*Patients <75 yrs motivated for each activity*			
Number of patients	347	141		1206	176	257
Age (years)	74.8 at FU	66.4 at FU		67 at surgery	70 (W) and 71 (M) at FU	70 (W) and 67 (M)
Activity						
Stationary cycling	24%	31%	86%	45%	51%	17%
Cycling	13%	18%	72%	15%	na	na
Stretching	17%	21%	85%	na	73%	63%
Swimming	22%	31%	79%	29%	35%	19%
Golf	2%	2%	100%	21%	18%	9%
Sailing	2%	3%	100%	na	0%	0%
Musculation	5%	4%	25%	17%	70%	66%
Dancing	3%	6%	33%	25%	43%	27%
Gymnastics	17%	16%	68%	2%	na	na
Hiking	26%	35%	80%	25%	na	na
Gardening	37%	52%	84%	na	57%	51%
Cross Country Skiing	11%	5%	44%	2%	7%	2%
Down Hill Skiing	6%	8%	62%	70%	5%	2%
Tennis	1%	1%	50%	2%	10%	5%
Running >500m	2%	2%	67%	1%	10%	5%
Soccer	-	-	-	0%	-	-
Rowing	-	-	-	3%	-	-
Canoeing	-	-	-	6%	-	-
Basketball	-	-	-	1%	-	-
Volleyball	-	-	-	1%	-	-
Iceskating	-	-	-	0%	-	-

Conclusion

This study demonstrates that satisfactory index is different from the patient point of view than from the physician. It demonstrates also that sports activities are not only dependent of the TKA itself but also from the motivation of the patient. Our results confirm that a good result for TKA is not systematically a “pain free” or “symptom free” knee but a knee that satisfies patient’s preoperative expectancies or main preoperative goals. The main clinical relevance is a strong need for information of the patient regarding his functional capabilities after TKA in order to match expectations and final results. This study reports a clear description of patient's possibilities to return to sport activities after TKA in motivated and non-motivated patients. It should help surgeons to give clear information to patients.

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Appendix

Circle appropriate number																	
Activities	Is this activity important for you ?					How many time do you practice this activity? *					Does your knee bother you during practice					I never practice	
	1: not important 2: minimal importance 3: moderate importance 4: important 5: very important					1:rare 2:occasionnal 3:regularly but not often 4: regularly and often 5: intensively					1: not at all 2: minimally 3: moderately 4: bother me 5: bother me a lot					1: because of my knee 2: for another reason	
1. Stretching	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2
2. Stationary cycling	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2
3. cycling	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2
4. Gym	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2
5. Musculation	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2
6. swimming	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2
7. Golfing	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2
8. Gardening	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2
9. Dancing	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2
10. Hiking	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2
11. Tennis-Squash	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2
12. Running > 500 m	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2
13. Squatting	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2
14. Kneeling	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2
15. Cross country skiing	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2
16. Downhill skiing	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2
17. Sailing	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2

3. What are the factors of residual pain after uncomplicated TKA?

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Abstract

Purpose: Residual pain during activities of daily living and/or at rest is a major cause of a patient's dissatisfaction after Total Knee Arthroplasty (TKA). The management of a painful TKA which has no obvious clinical or radiological explanation, requires further investigation with more sensitive imaging modalities (CT scan and bone-scan) and hematological tests. It is often challenging for the physician to determine what level of pain warrants these more complex and expensive medical examinations. A precise knowledge of the natural history of postoperative pain following TKA, is therefore of fundamental importance.

Methods: We reviewed the literature and highlighted the studies that investigated the evolution of pain after uncomplicated TKAs and the impact of demographic and psychosocial variables on a postoperative painful TKA.

Results: Factors that are associated with a more painful knee include female sex, a younger age at the time of surgery, and a higher than normal depressive or anxiety state. In particular the Pain Catastrophizing Scale (PCS), a scale that quantifies a patient's negative or exaggerated orientation to pain, appears to significantly influence a patients outcome after TKA.

Conclusion: The identification of these high risk patients is critical so that a surgeon can provide detailed pre-operative education in order to give these patients a realistic expectation of their possible satisfaction following TKA.

Introduction

Total knee arthroplasty (TKA) is a safe and reliable surgical procedure for the treatment of pain and disability in patients with primary or secondary osteoarthritis of the knee. Despite the increasing survival of TKAs, due to innovations in biomaterials, design and surgical techniques, the rate of satisfaction following TKA reported in the literature varies from 75% to 89%[4-11]. Three main factors influence a patient's satisfaction after surgery: (i) the functional outcome, (ii) the level of residual pain and (iii) the preoperative expectations[4, 6, 12-14]. The latter is of particular importance as a good result following TKA is not universally a "pain free" or "symptom free" knee but a knee that meets a patient's preoperative expectations and goals[4, 15-18]. As a result, evaluating the outcome after TKA can be difficult and criteria of satisfaction may differ between patients and physicians[19, 20].

As continuing pain is not uncommon after apparently uncomplicated TKA, it is often challenging to determine what level of discomfort is acceptable and what level of pain warrants complex and expensive imaging examinations such as bone scan or CT scans and haematological tests.

A precise knowledge of the natural history of postoperative pain following TKA, is therefore of fundamental importance. The goal of this review was to analyse the evolution and the factors influencing the residual pain after "uncomplicated" TKA, i.e. well performed TKAs' without septic or mechanical complications.

How do you quantify pain?

Quantifying pain is particularly challenging, as many psychological factors may influence the result. The level of pain following TKA is currently evaluated through «clinician completed scores» such as the Knee Society Score[20] and the Hospital for Special Surgery Score[21] or through «patient completed forms», such as the Oxford Knee Score[22] the Western Ontario and MacMaster (WOMAC) score[23] or the Knee Injury & Osteoarthritis Outcome (KOOS) score[24]. The use of Visual Analog Scales is a commonly used and validated technique. The McGill Pain Questionnaire (MPQ) is a more sophisticated and complex self-administred Questionnaire, described by Melzack in 1971[25]. In the MPQ, specific adjectives used by patients to describe their pain were brought together and categorized, and were scaled on a common intensity dimension. It provides a standardized measure of the affective and sensory dimensions of pain. A short form (SF-MPQ) was described and validated by Melzack in 1987[26]. It consists of 15 adjectives describing sensory, affective and evaluative aspects of the pain experience. The three measures included in the SF-MPQ are: (i) the Pain Rating Index (PRI), which rates 15 adjectives that best describe the current pain; (ii) a visual analogue scale and (iii) the Present Pain Intensity, which rates the overall intensity of the total pain experience on a numerical rating scale, from 0 (no pain) to 5 (excruciating pain). Interestingly, Forsythe observed a parallel evolution of PRI, VAS and PPI postoperatively after TKA[3].

What is the residual pain after a well performed, uncomplicated TKA?

The range of pain reported in a series of "uncomplicated" TKAs' can theoretically be used to define what is the "acceptable" or "non pathologic" level of residual pain after TKA. However, these studies can be biased as the validity of the criteria "uncomplicated" depends on the medical examinations used for the investigation.

The Pain score of the WOMAC evaluates the level of pain with five items: pain during walking on flat ground, pain during ascending and descending stairs, pain while standing, pain during lying or sitting and pain at rest at night[23]. In a continuous multicentre series of 347 non selected TKA[4], we reported a mean WOMAC pain score, from 0 (best) to 10 (worst) of 1.4±1.7 (0-8). None of these patients had been revised and none was planned for revision. Patients with a contralateral TKA during the studied period were also excluded. Expressed on a 0-100 scale were 0 = worst score and 100 = best score, our mean pain score was 86±17 (range; 20 to 100). It was 90.0 (30 to 100) in the satisfied patients and 70.0 (20 to 100) in the dissatisfied patients ($p<0.0001$). In this series, 62% of our patients were totally pain free during walking, 35% while climbing or descending stairs, 66% at rest in bed, 61 when sitting and 43% while standing (Figure 1). When patients evaluate the pain during daily activities, 45% reported severe pain while kneeling, 39% while squatting and 21% while standing. Among sport participants, 40% complained of pain while running, 10% during cross-country skiing and 7% during downhill skiing (Figure 2). However, pain during activity did not seem to influence the participation of motivated patients[4]. Recently, Bourne compared the WOMAC pain score, from 0 (worst) to 100 (best) in a THR and a TKR cohort of patients[27]. Patients were obtained from the Ontario Joint Replacement Registry and selected with similar criteriae (no revision and no second joint arthroplasty during the study period). He observed a lower score preoperatively in THA compared to TKA (41.6 versus 43.4, $p=0.004$), but a higher score in THA at one year post surgery (91.1 versus 86.2, $p<0.0001$). Moreover, in this comparative study, pain while walking was a source of dissatisfaction in 4.9% of the patients after THA and 7.3% after TKA (p<0.0001). Pain during climbing or descending stairs was a source of dissatisfaction after THA in 7.4% of the patients and in 13.3% after TKA (p<0.0001).

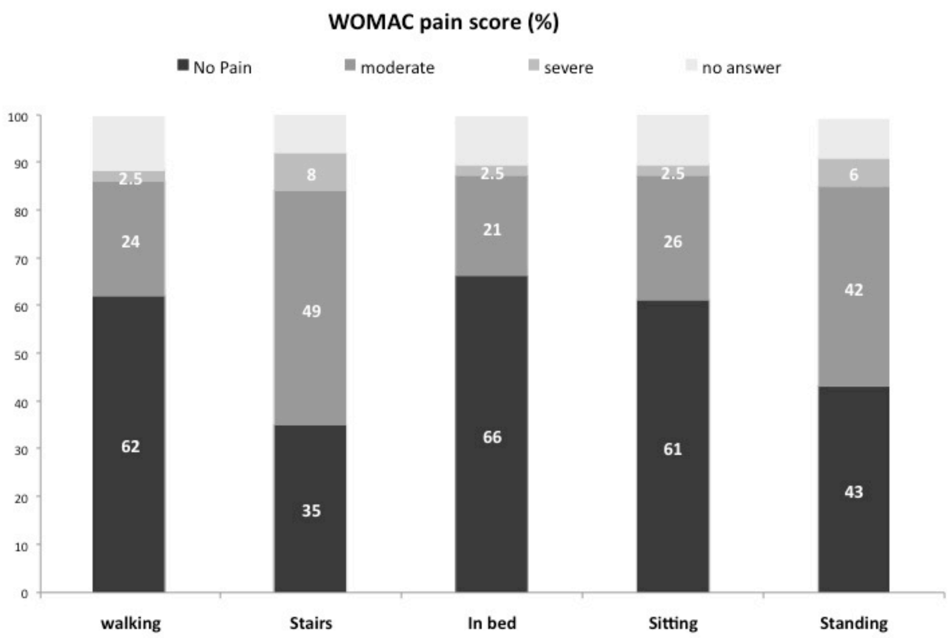

Figure 1: This graph represents the percentage of patients with residual pain after TKA (no pain, moderate pain, severe pain) during activities of daily living analyzed with the WOMAC pain score. From Bonnin[4].

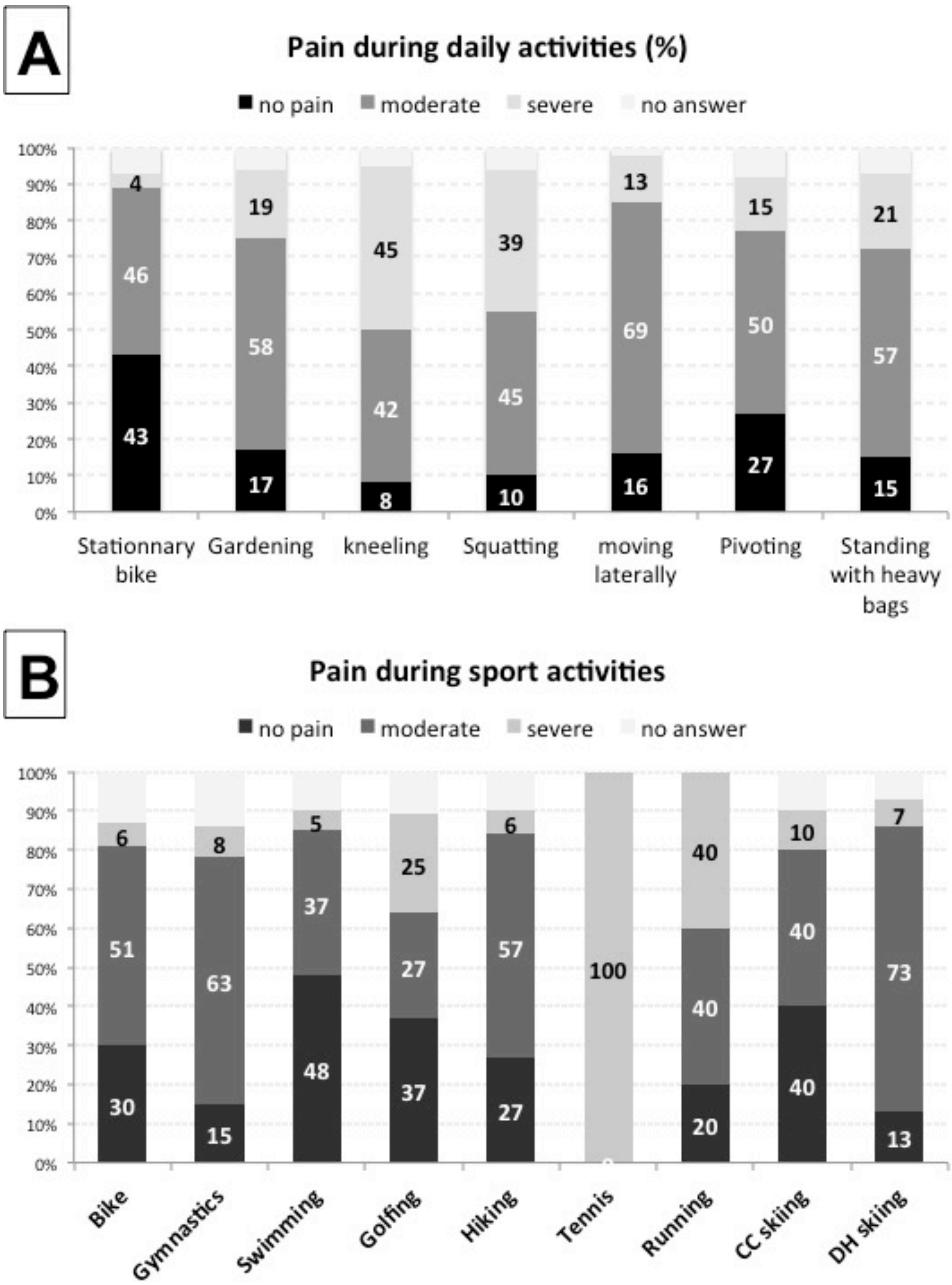

Figure 2: This graph represents the percentage of patients with residual pain after TKA (no pain, moderate pain, severe pain) in activities of daily living (A) and during sport activities (B). From Bonnin[4].

What is the evolution of the pain after uncomplicated TKA?

Recently, it has been shown that after TKA, even if the main pain improvement occurs during the first postoperative year, pain continues to decrease up to five years following surgery[1, 2]. Brander quantified the decrease of pain, via the Visual Analogue Scale from 0 (no pain) to 100 (worst pain conceivable), in the first postoperative year of a series of uncomplicated TKA[2]. In the series of 149 knees (mean age, 66 years; 55.2% women), the mean preoperative pain level was 52.6±24.4. Postoperatively, it was 36.8±21.8 after one month, 25.4±21.3 after three months, 20.5±20.1 after six months, and 16.6±21.0 after one year. The pain level was superior to 40 on VAS in 72.3% of the patients preoperatively and in 44.4% of the patients after one month, 22.6% after three months, 18.4%, after six months. One year after surgery twelve patients (13.1%) reported a pain level greater than 40 (mean level 63±18, range 41 to 97). Interestingly, in another study published four years later, Brander re-evaluated these twelve patients at five years of follow-up[1] and observed a progressive improvement over time. The mean pain level was now 29±33 (20 to 80) and among the eight reevaluated patients, six were satisfied with the procedure. Globally, the mean VAS at five years in the overall series was 11.

Forsythe evaluated also the postoperative pain in a cohort of fifty-five patients with uncomplicated TKA[3]. The authors observed a parallel evolution of Pain Rating Index (PRI), Visual analog scale (VAS) and Present Pain Intensity (PPI) postoperatively. The PRI was 17.8±8 preoperatively and 10.1±8, 8.4±9 and 7.6±9 respectively at three, 12 and 24 months. The mean VAS level, from 0 (no pain) to 100 (worst pain conceivable), was 68±19 preoperatively, 33±27 at three months, 27±30 at one year and 22±23 at 2 years. The PPI was 2.9±1 preoperatively and 1.5±1, 1.2±1 and 1.1±1 respectively (Figure 3). With all measurements, no improvement was observed after three months and which point the pain reached a plateau[3].

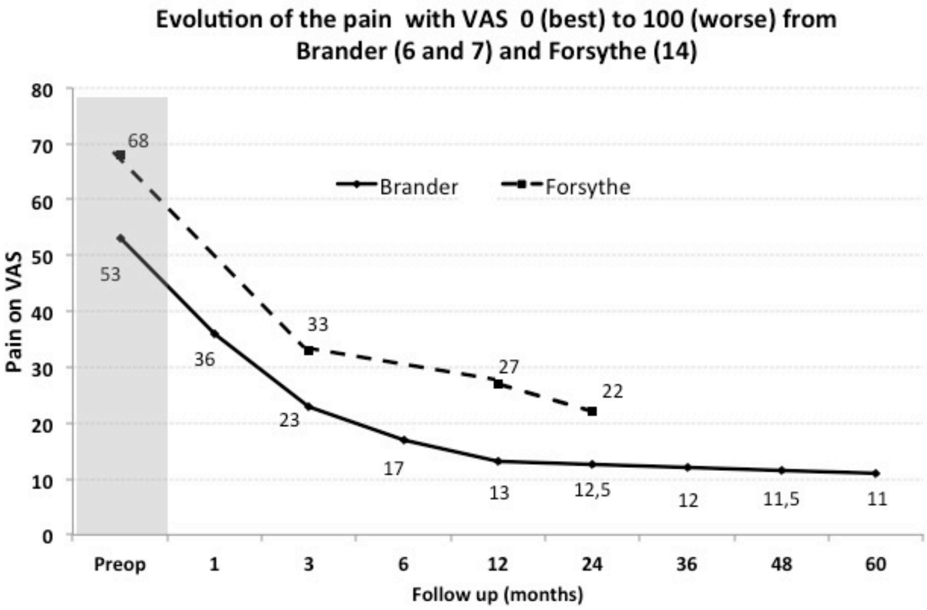

Figure 3: Evolution of the postoperative pain, quantified with VAS, in two series of uncomplicated TKAs. Modified with authorization from Brander[1, 2] and Forsythe[3].

Does a patients characteristics influence residual pain after TKA?

Researchers have paid special attention in the last decade to whether residual pain after TKA may be determined by a patients characteristics[28]. This aspect is of special interest for the surgeon firstly because it means that the pain may be due to problems unrelated to the implants themselves. Secondly, it can help the medical team to prevent unsatisfactory results, with preoperative education and careful patient selection. Lastly it can help to improve the result in patients with disappointing results, through improved care. Among patients characteristics, the age at surgery, the gender of the patient, the level of the preoperative pain, the depressive or emotional status of the patient have been particularly analyzed.

We reviewed the literature and highlighted the studies that investigated the impact of demographic and psychosocial variables on a postoperative painful TKA, in order to understand if the pain could be attributable to a patient's perception of pain. In the literature, one of the most analyzed variables is the influence of preoperative pain. Some authors suggest a trend of a worse clinical outcome in patients who have higher preoperative pain[29-32]. However, others have observed that preoperative pain influences functional outcome but not pain[1-3, 33]. Singh analyzed the influence of preoperative modifiable (BMI and comorbidities) or non-modifiable factors (age and gender) on pain and function at two and five years following TKA. They concluded that both, modifiable and non-modifiable predictors influenced the risk of a functional limitation and a walking-aid dependence after primary TKA.

1 – Level of preoperative pain

A high degree of preoperative pain is frequently reported as an important predictor of residual pain after TKA[29-32]. However, these findings have not been confirmed by other recent work.

Brander observed a positive correlation between the preoperative level of pain, analyzed on Visual Analog Scales, and the KS-function score after one year ($p<0.01$) and five years ($p=0.015$). However, no correlation was found with the postoperative VAS pain level, neither after one year, nor after 5 years[1, 2]. In the same way, Forsythe did not found any correlation between preoperative and postoperative pain scores after two years, neither with the Pain Rating Index of the McGill Questionnaire ($p=0.57$), nor with the VAS evaluation ($p=0.22$)[3]. With the same evaluation tools, Singh found no correlation at two years ($p=0.53$ and 0.46 respectively) and five years ($p=0.14$ and 0.12 respectively)[33].

2 – Gender of the patient.

The correlation between gender and residual pain after TKA is controversial (Table 1). Ritter, while comparing the outcomes of 4.379 TKA performed in women to 2.947 performed in men five years after surgery, observed a better pain score in men compared to women both preoperatively ($p=0.0005$) and postoperatively ($p<0.0001$). However, he noted that the pre-postoperative improvement of the pain score was equivalent (48.5 in men and 47.2 in women, $p=0.54$)[34]. Singh outlines that *"women are 45% more likely to report moderate to severe pain two years after TKA"*, with 9% painful TKAs in 2.750 women versus 6.6% in 2181 men, ($p=0.004$). However, five years after surgery, this difference was no longer significant (7.9% in women versus 6.5% in men, $p=0.23$)[33]. Lingard in her prospective observational study of primary TKA's from centers in the United States, the United Kingdom and Australia, found no differences at follow-up in terms of WOMAC function and pain scores, despite the marked differences at the preoperative assessments[35]. Both Lingard[32] and Fortin[36] noted that women wait longer than men to undergo surgery, and this delay may explain the lower preoperative scores. Interestingly, Fortin suggested that a better outcome may be associated with earlier surgery[36]. Elson comparing outcomes in 199 women and 175 men observed 7% of painful knees at followup in each group[37]. Roth, analyzing the pain during the three postoperative days didn't observe gender difference[38].

Table 1: This table summarizes the conclusions of publications which analyze the influence of the gender, the age at surgery and the level of the preoperative pain on the residual pain after TKA.

Author	Year	Gender	Age at surgery	Level of preop pain
Fortin et al.	1999	Not studied	0	+
Jones et al.	2001	0	0	+
Brander et al.	2003/2007	Not studied	Not studied	0
Lingard et al.	2004	0	0	+
Fitzgerald et al.	2004	0	patients <75 more painful	+
Elson et al.	2006	0	patients <60 more painful	Not studied
Roth et al.	2007	0	0	Not studied
Ritter et al.	2008	More pain in Women	Not studied	Not studied
Singh et al.	2008	More pain in Women at 2 yrs but not at 5 yrs	patients <60 more painful at 2 yrs but not at 5 yrs	0
Forsythe et al.	2008	Not studied	Not studied	+

Abbreviations: 0, no influence; +, positive correlation between preoperative pain and residual pain

3 – Age at surgery

Studies have shown that younger patients have more residual pain after TKA and the explanation of such an observation is still unclear. Possible explanations include higher activity levels in young patients, lower level of expectations in older patients, higher pain tolerance in older patients and more peripheral neuropathy in older patients[33]. Two years after surgery, Singh observed that 10.3% of the patients who were younger than 60 at the time of surgery complained of moderate or severe pain, which was significantly higher than in patient's who were 60-70 (6.3%, $p<0.001$) or the 70-80 (7.4%, $p=0.01$). Five years after surgery the difference was still significant with 10.2% of moderate to severe pain in patients less than 60 years and 6.2% in the 60-70 year old patients ($p=0.02$)[33]. Elson found 17% of painful TKAs in patients operated on before 60 years of age, compared with 6% in the 60-70 year old patients and 4% in patients older than 70 at surgery ($p<0.01$)[37]. Fitzgerald, using the bodily pain score of the SF-36, observed that patients older than 75 years at surgery had better outcome at 1 month, 6 months and 12 months after surgery[29].

4 – Psychological factors

During the last 20 years some authors have paid particular attention to the influence of psychological factors such as depression, anxiety or psychological distress on the final outcome of TKAs. It has been estimated that 25% of the patients operated on for a TKA or THA complain of psychological distress, which potentially can worsen pain and function outcome[39]. Quantifying depression and anxiety can be done through General Health Questionnaires, such as the mental health scale of the SF-36 (SF36-MH)[35, 40, 41] or via specific scales: The State-Trait Anxiety Index (STAI) provides a standardized measure of anxiety[1, 42]. The Beck Depression Inventory (BDI) is a standardized measure of depression[43]. The Perceived Stress Scale is a brief self-report questionnaire that assesses an individual's perception of current life stress[44].

One year after TKA, Brander observed a correlation between the VAS pain level and the preoperative Anxiety score (STAI) ($r=0.38$ and $p<0.05$) and an even higher correlation with the preoperative Depression score (BDI) ($r=0.43$ and $p<0.01$). No correlation was found with the Perceived Stress Scale. From this first study the author concluded that *˝untreated depression preoperatively, or even higher than normal depressive symptoms, is an independent risk for severe postoperative pain and may explain a subset of those patients with unexplained pain after surgery˝*. The same authors re-analyzed in 2007 the outcome of the initial series[2]. Surprisingly, they observed that preoperative depression did not predict a lower pain score after five years but did predict a lower function score as evaluated with the KS-function score (p=0.0004).

Lingard compared the WOMAC pain scores two years after TKA, in two cohorts of «distressed» and «non distressed» patients. In this study, the definition of «distress» was a SF36-MH score inferior to the median score of those seeing mental health clinicians[39]. Distressed patients had a lower WOMAC pain score than non distressed patients (75.4 versus 79.5, p=0.029). However, the preoperative score was also lower in the distressed patients (36.7 versus 44.3 respectively, p=0.0002) and the pre-postoperative increase was not significant (35.5 versus 33.9 respectively, p=0.44). Interestingly, the WOMAC function score was equivalent in the two groups two years after surgery (67.3 versus 68.9 respectively, p=0.4). The authors concluded from this study that *″postoperative changes in pain scores do not differ between patients with and those without distress. Physical function outcome and change scores also do not differ significantly between distressed and non-distressed patients″. The* authors emphasize that psychological distress is reversible and that chronic pain due to joint arthritis can also be a source of distress. Therefore, in this study, mental status of "distressed" patients markedly improved following surgery, while it stay essentially the same in the non distress patients.

Sullivan suggested in 1995 a particular questionnaire, the Pain Catastrophizing Scale (PCS) in order to quantify patients negative or exaggerated orientation to pain[33]. It is a 13-item self report scale rated on a scale from 0-4 and has three different categories: Rumination (tendency to focus excessively on pain sensations), Magnification (tendency to exaggerate the threat value of pain sensations) and Helplessness (tendency to perceive oneself as being unable to control pain symptoms). The PCS is a 13-item scale with scores ranging from 0 (no catastrophizing) to 52 (severe catastrophizing).

Forsythe observed that patients with persistent pain at 24 months had a significantly higher preoperative PCS, suggesting a psychosocial explanation of postoperative pain[3]. Furthermore, they found that psychological variable of the PCS did not significantly change after TKA. This may be related to the increased attention and sensory flow of pain signals as demonstrated by Crombez in an experimental study[45].

Riddle investigated the influence of the preoperative PCS on the WOMAC pain score, in a cohort of 140 TKA patients six months after TKA. In this study PCS was the only predominant predictor of poor pain outcome[21]. Patients with PCS scores superior or greater than 16 had an increased risk of poor outcome (less than 50% improvement) of 2.67 times compared with patients with PCS scores of 15 or less. Because behavioral treatments have proven to be efficient for reducing pain catastrophizing, the author suggests the need for the improved identification of these high risk patients so that they can get better psychological preparation[46].

Conclusion

In conclusion it is important for a surgeon to have an understanding of the factors that can contribute to a poor result in patients who have a non-infected, well-fixed and well-aligned total knee replacement. Factors that are associated with a more painful knee include female sex, a younger age at the time of surgery (<60), and a higher than normal depressive or anxiety state. In particular the Pain Catastrophizing Scale (PCS), a scale that quantifies a patient's negative or exaggerated orientation to pain, appears to significantly influence a patients outcome after TKA. The identification of these high risk patients is critical so that a surgeon can provide detailed pre-operative education in order to give these patients a realistic expectation of their possible satisfaction following TKA. Further research is required to fully assess the effect that pre-operative behavioral therapy has on this group of patients in terms of improving their perception of pain after TKA.

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4. Mediolateral oversizing influences pain, function, and flexion after TKA

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Abstract

Purpose: Manufacturers of TKA have introduced narrower femurs to improve bone-implant fit. However, few studies have reported the clinical consequences of mediolateral oversizing. Our hypothesis was that component oversizing negatively influences the results after TKA.

Methods: One hundred and twelve prospectively followed patients with 114 consecutive TKA (64 females and 50 males) were retrospectively assessed. The mean age of the patients was 72 years (range, 56 to 85 years). The dimensions of the femur and tibia were measured on a preoperative CT scan and were compared with those of the implanted TKA. The influence of size variation on the clinical outcomes one year after surgery was assessed.

Results: Mediolateral overhang was observed in at least one area in 66% of the femurs (84% in females and 54% in males) and 61% of the tibia (81% in females and 40% in males). Twenty-two patients presented no overhang in any area and 16 had overhang in all studied zones. The increase in the Pain and KOOS scores were 43±21 and 36±18 in the patients without overhang and 31±19 and 25±13 in patients with overhang (p=0.033 and p=0.032). Knee flexion was 127°±7 and 121°±11, respectively. Regression and latent class analysis showed a significant negative correlation between overall oversizing and overall outcome.

Conclusions: This study confirms that oversizing may lead to worse clinical results in TKA. The clinical consequences are that surgeons should pay attention not to oversize implants during implantation and that oversizing should be ruled out in case of so called unexplained pain.

Introduction

Recent anatomical studies have shown that the size and shape of the femur and tibia at the knee vary significantly among individuals, most notably between males and females[1-3]. As a consequence, certain manufacturers of total knee arthroplasty (TKA) prostheses have increased their size range and introduced narrower femurs in an attempt to provide a better fit between the bone and implant and to prevent peripheral component overhang[4-8]. Oversizing the implant can theoretically compromise the clinical outcome by increasing tension and capsular/ligamentous friction on the implants. However, its actual clinical consequences have not been sufficiently studied. Mahoney et al. showed that femoral component overhang increased the risk of residual pain after TKA[9], but the use of narrower, femoral implants did not always improve the results[6, 10-13]. Whether these narrower implants are warranted remains under debate.

The objective of the present study was to assess the clinical consequences of femoral and tibial component overhang. The study aimed to quantify the association between mediolateral femoral and tibial sizing and clinical outcomes such as residual knee pain, function, and flexion. Our primary hypothesis was that component overhang in relation to the bone contours negatively influences the clinical result in terms of pain, function and joint range of motion. Our second hypothesis was that there is an oversizing threshold beyond which the negative effect is observed.

Materials and Methods

In order to test the hypotheses, a series of 255 consecutive patients undergoing primary TKA by a single surgeon between January, 2008 and June, 2009 were retrospectively analyzed. In our institution, a CT scan is performed as part of a systematic preoperative work-up for TKAs[2], and all our patients are prospectively followed. This study was designed to measure the size of the femur and the tibia on the preoperative CT scan and to compare these measurements with the size of the prosthesis implanted. We then sought to determine whether a relation existed between the size difference (under- or oversizing) and the result at 1 year postoperative, analyzed using the KOOS score and knee flexion.

Thirty four patients in whom CT analysis of bony contours could be difficult were excluded from this study: patients with a history of previous knee surgery or fracture around the knee and patients who demonstrated a preoperative loss of full extension greater than 10°. Seventy nine patients in whom functional evaluation could be biased, were also excluded: patients with inflammatory arthritis, patients older than 85 years, patients who had a postoperative complication necessitating revision, patients who had undergone surgical intervention of the contralateral knee less than a year before evaluation, or who had a medical event that prevented the functional assessment. A series of 142 patients was used for this study. All patients signed an informed consent form and the institution ethics committee authorized the study. Twenty-six patients were also excluded because of an incomplete preoperative or postoperative KOOS questionnaire and four patients because their CT scan could not be used due to artifacts.

In all, 114 knees (64 females and 50 males) in 112 patients were included in the study. The indication for TKA was medial compartment osteoarthritis in 80 knees, lateral compartment osteoarthritis in 16 knees, combined osteoarthritis in 8 knees, patellofemoral osteoarthritis in

6 knees, and spontaneous necrosis of the medial condyle in four knees. Demographic characteristics of the series are mentioned in Table 1.

Table 1: Preoperative demographic characteristics of the series

	Series Mean ± SD	(min - max)	**Men** Mean ± SD	(min - max)	**Women** Mean ± SD	(min - max)	***p values*** [1]
Age (years)	72 ± 7	(56 - 85)	71 ± 7	(56 - 85)	72 ± 7	(56 - 85)	*n.s.*
Weight (kg)	81 ± 15	(45 - 125)	87 ± 15	(62 - 125)	76 ± 14	(45 - 105)	*0.0001*
Height (cm)	168 ± 10	(144 - 194)	175 ± 7	(155 - 194)	162 ± 7	(144 - 178)	*0.0001*

[1] Between women and men (Student T test)

CT scan has been routinely performed as part of a systematic preoperative work-up for patients set to undergo TKA, in order to optimize rotational alignment of the femoral component with the transepicondylar axis. The CT scans were taken using a 64-slice multidetector scanner (Siemens® Sensation, Munich, Germany). The measurements were taken by an experienced operator (AS), using OsiriX software with a technique that has previously been described[2]. For each knee, the mediolateral diameter was measured in three zones on the femur and in one zone on the tibia (Figure 1). The measurements were taken at the level of the tibial cut and at the level the distal femoral cut made during the operation, which was documented in the surgical report. Each of these dimensions was compared to the corresponding dimension of the prosthetic component provided by the manufacturer (see Appendix). The difference between the preoperative and postoperative dimensions ("size variation") was deemed positive in cases of implant oversizing and negative in cases of undersizing. Dimensions were measured in millimeters, with one decimal. For each dimension, the cortex was included in the measurement. A special attention was paid not to include osteophytes in the measurements. We defined oversizing as a difference greater than 0 mm. To assess the accuracy of the measurements we (MB, AS and LB) blindly repeated the measurements on twenty sets of CT scans. A high level of intra and inter-observer reliability with errors of the mean always less than 1.5mm was found.

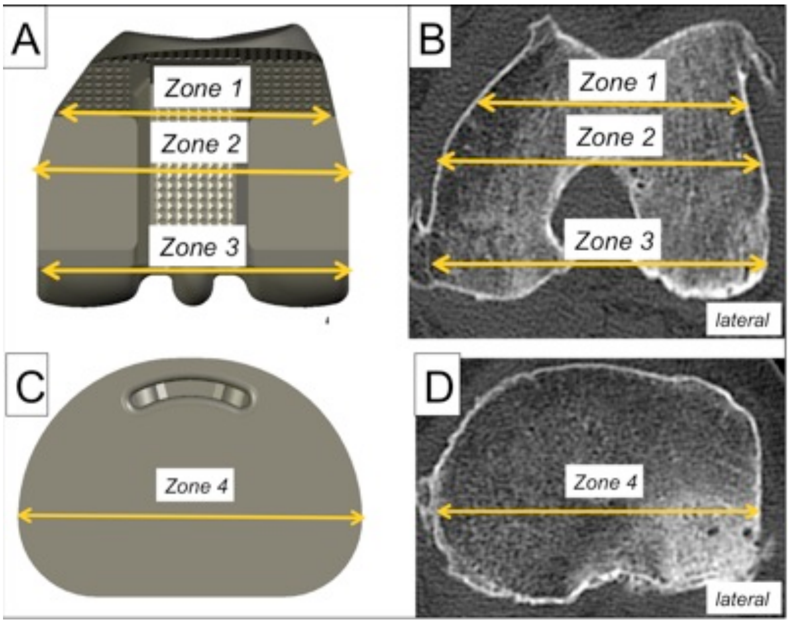

Figure 1: Three reference zones were defined on the femoral implant (A): zone 1, corresponding to the posterior part of the anterior chamfer, was located at a variable distance from the posterior bicondylar line (BCL) depending on the implant size (39.4–48.5 mm; see Appendix). Zone 2 was located at a variable distance from the posterior bicondylar line (BCL) depending on the implant size (26–36 mm; see Appendix), but was directly posterior to the point where the implant began to narrow. Zone 3 corresponds to the posterior condylar bone cut, situated 10 mm from the BCL. On the CT scan (B), the analysis was done on the axial cut located at the level of the distal femoral cut made at the time of surgery (10 mm from the most distal point of the medial condyle). The bone dimensions corresponding to the three zones defined were measured: zone 1, 10 mm from the BCL, zone 2 and zone 3, at the distance corresponding to the size of the implanted prosthesis.

On the tibia, the mediolateral dimension (zone 4) was used as the reference (C). On the CT scan, the measurement was taken on the axial cut located at the bone cut made at the time of surgery (D). The transverse, mediolateral dimension was measured.

Before surgery, each patient completed a KOOS functional assessment self-questionnaire at home in its validated French version[14]. After surgery, the patient completed a new KOOS self-questionnaire at home one year after the TKA. A follow-up visit 1 year after surgery was conducted by the senior rehabilitation physician, who was blinded to the size study. Maximum passive flexion (MPF) of the knee was measured at this time using a goniometer on the patient seated at the end of the examination table[15].

The prosthesis used was a posterior, stabilized implant with a fixed, tibial tray (HLS-Noetos, Tornier SA, Montbonnot, France, FDA approved device), which included six sizes and whose femoral and tibial aspect-ratio was close to other currently used implants (see Appendix)[2, 3]. All the prostheses were implanted using the same technique. Specifically, a medial parapatellar approach was used to evert the patella. The tibia was cut first, followed by the femur with a posterior reference. The tibial and femoral cuts were orthogonal to the mechanical axis so as to obtain a 180° axis. Rotation of the femoral component was aligned along the surgical transepicondylar axis, localized on the preoperative CT scan for each patient. Rotation of the tibial component was aligned with respect to the center of the anterior tibial tuberosity. The size of the components was determined based on the instrumentation so as to prevent any notch from being created along the anterior femoral cortex. The patella was resurfaced in such a way as to reproduce the preoperative patellar thickness. All the components were cemented (CMW3, DePuy, Warsaw, IN, USA). The same rehabilitation protocol was followed for all patients[16].

Statistical analysis

The difference of oversizing between men and women was tested using a Student T test. The effect of size variation (under- or oversizing) in the four zones defined was analyzed with respect to pain, function, and flexion one year after implantation. To limit the risk of error related to multiplicity of statistical tests, three main variables were studied: pain was assessed using the pain subscore (P) of the KOOS score, overall function by the overall KOOS score, and flexion by the angle of MPF[17, 18]. For each patient, both the postoperative score and the score improvement were studied. The KOOS subscore values are presented in the Appendix. The analysis was carried out in four steps: (1) for each zone studied, two groups were compared: the oversized prosthesis group (size variation ≥ 0 mm) versus the normal or undersized prosthesis group (size variation < 0 mm) using the unilateral, nonparametric Mann-Whitney test. Additionally, we compared the subgroups of patients in whom each zone was oversized versus those without any oversized zone. (2) The nonlinearity of the relationship was tested using smoothing splines and fractional polynomials[19]. To test nonlinearity, a F-test was used based on an analysis of deviance between the models in which sizing was introduced linearly and the model in which sizing was introduced nonlinearly (degree of freedom=4). (3) Linear regression models were then used to test the relation between MPF, increase of pain score or increase of KOOS score and size variation. (4) Finally, a multivariate and latent-class analysis was performed[20]. This analysis included four observed variables (size variation in the four defined zones) that reflected a latent variable representing the global "prosthetic fit", and two other observed variables (pain score and flexion) that reflected another latent variable representing the global "post-operative outcome". The relationship between the two latent variables was explored through a Spearman correlation. All analyses were performed using R software (latent class analysis was performed using the sem package from R software).

Results

In the femur, a medial-lateral prosthesis overhang greater than 0 mm was observed in 66% of the knees in zone 1 (76 knees), 30% in zone 2 (34 knees), and 23% in zone 3 (26 knees). This proportion was 84%, 48%, and 34% in females and 54%, 30%, and 14% in males, respectively. For the tibia, medial-lateral overhang was found in 61% (70 knees), 81% in females and 40% in males. Only twenty-two patients (18 men, 4 women) presented no overhang in any area and 16 had overhang in all zones (3 men, 13 women). For all the sizes studied, oversizing was significantly greater in females (Figure 2 and Table 2).

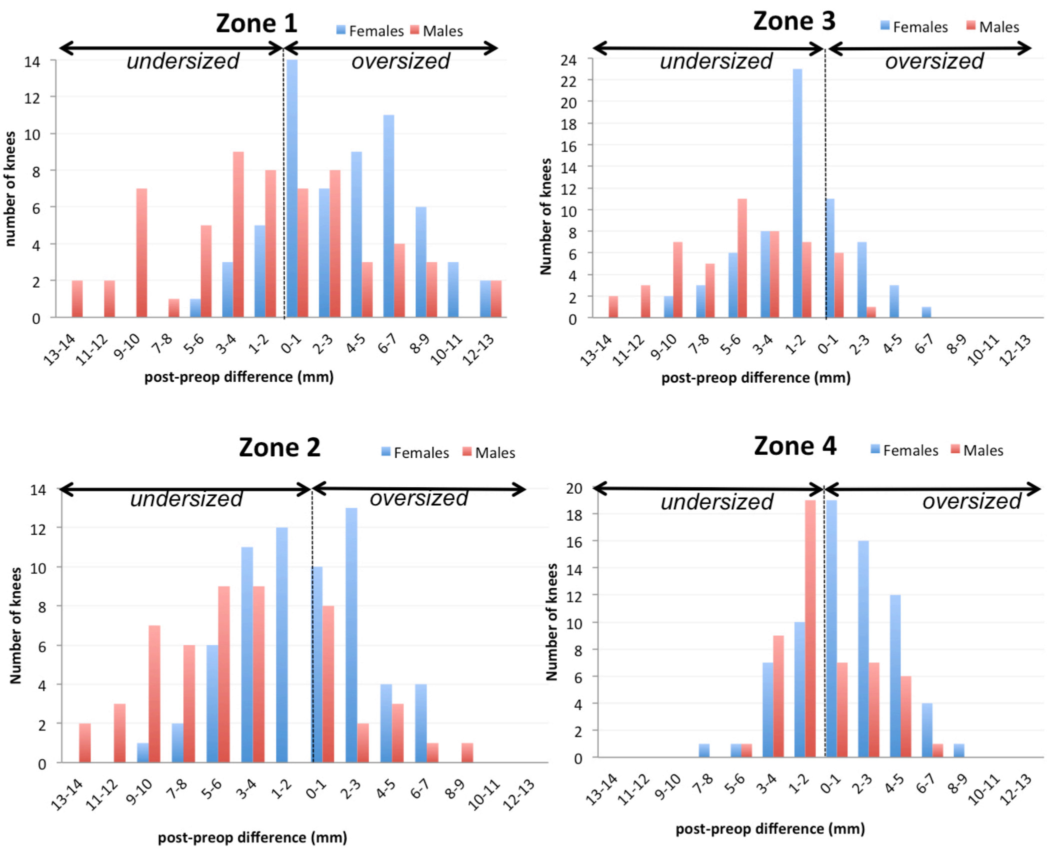

Figure 2: These histograms represent the distribution of the size variation (X axis) in the four zones studied in females (blue columns) and males (red columns).

Table 2: Difference between preoperative dimensions (CT scan) and implant dimensions (mm)[1] on the four studied zones

	Series Mean ± SD	(min - max)	Men Mean ± SD	(min - max)	Women Mean ± SD	(min - max)	*p values*[1]
Zone 1	2.2 ± 5	(-10 - 13)	0.7 ± 5	(-7 - 11)	3.3 ± 4	(-10 - 13)	*n.s.*
Zone 2	-2.2 ± 5	(-16 - 8)	-4.2 ± 5	(-16 - 8)	-0.7 ± 4	(-10 - 7)	*<0.001*
Zone 3	-3.2 ± 4	(-16 - 7)	-5.4 ± 4	(-16 - 2)	-1.5 ± 3	(-12 - 7)	*<0.001*
Zone 4	0.9 ± 3	(-7 - 8)	-0.3 ± 3	(-6 - 6)	1.9 ± 3	(-7 - 8)	*<0.001*

[1] Negative value means undersizing
[2] Between women and men (Student T test)

Preoperatively, women had a significantly lower flexion than males and lower Pain score, but preoperative KOOS score was not significantly different between males and females (Table 3). One year after surgery, pain score, KOOS score and knee flexion were lower in females. The gain of KOOS score was significantly lower in females but the gain of pain score was not significantly different (Table 4).

Table 3: Preoperative scores

	Series Mean ± SD	(min - max)	Men Mean ± SD	(min - max)	Women Mean ± SD	(min - max)	*p values*[1]
Pain score	45 ± 15	(0 - 94)	49 ± 15	(8 - 94)	42 ± 15	(0 - 69)	*0.030*
KOOS score	36 ± 11	(6 - 81)	38 ± 12	(12 - 81)	34 ± 11	(6 - 55)	*n.s.*
Flexion (˚)	105 ± 10	(60 - 125)	107 ± 8	(60 - 125)	102 ± 10	(60 - 120)	*0.040*
FTA (˚)	176 ± 5	(160 - 194)	175 ± 5	(165 - 186)	177 ± 6	(160 - 194)	*0.003*

[1] Between women and men (Student T test)
Abbreviation: FTA, Femorotibial angle measured on the long leg X-Rays from the mediazl side (<180° means varus deformity)

Table 4: Postoperative scores

	Series Mean ± SD	(min - max)	Men Mean ± SD	(min - max)	Women Mean ± SD	(min - max)	*p values*[1]
Pain score	79 ± 18	(28 - 100)	84 ± 17	(28 - 100)	75 ± 18	(36 - 100)	*0.005*
KOOS score	64 ± 17	(24 - 98)	71 ± 17	(31 - 98)	59 ± 16	(24 - 97)	*<0.001*
Flexion (˚)	122 ± 10	(95 - 140)	125 ± 8	(100 - 140)	121 ± 11	(95 - 140)	*0.038*
FTA (˚)	178 ± 3	(172 - 186)	177 ± 3	(172 - 183)	179 ± 3	(173 - 190)	*0.028*
Increase in Pain score	34 ± 19	(-14 - 83)	35 ± 19	(-11 - 75)	32 ± 19	(-14 - 83)	*n.s.*
Increase in KOOS score	29 ± 16	(-16 - 68)	33 ± 17	(-6 - 68)	25 ± 15	(-16 - 57)	*0.018*

[1] Between women and men (Student T test)
Abbreviation: FTA, Femorotibial angle measured on the long leg X-Rays from the mediazl side (<180° means varus deformity)

Oversized patients in zone 1 had significantly lower pain score at follow-up compared with undersized patients and showed less improvement in the pain score. Patients with oversizing in zone 3 showed less improvement in the KOOS score at follow-up and had significantly lower postoperative flexion. Oversized patients in zone 4 had significantly lower postoperative flexion (Table 5 and 6).

Table 5: Effect of size variation in each zone on postoperative pain score, KOOS score and knee flexion

	Under-sized		**Over-sized**		
	Mean ± SD	(min - max)	Mean ± SD	(min - max)	***p values*** [1]
Pain score					
Zone 1	82.5 ± 17.4	(27.8 - 100)	76.9 ± 18.1	(36.1 - 100)	*0.034*
Zone 2	79.8 ± 18.7	(27.8 - 100)	76.3 ± 16.4	(38.9 - 100)	*n.s.*
Zone 3	79.5 ± 18.7	(27.8 - 100)	76.2 ± 15.8	(44.4 - 100)	*n.s.*
Zone 4	81.1 ± 18.4	(36.1 - 100)	77.3 ± 17.8	(27.8 - 100)	*n.s.*
KOOS score					
Zone 1	67.6 ± 18.0	(31.3 - 97.0)	62.8 ± 16.7	(24.3 - 97.9)	*n.s.*
Zone 2	65.5 ± 17.5	(24.3 - 97.9)	61.7 ± 16.7	(25.0 - 94.1)	*n.s.*
Zone 3	64.8 ± 17.8	(24.3 - 97.9)	62.9 ± 15.4	(32.6 - 94.1)	*n.s.*
Zone 4	67.7 ± 16.8	(32.6 - 97.9)	62.3 ± 17.3	(24.3 - 97.0)	*n.s.*
Knee flextion					
Zone 1	124.6 ± 8.3	(105 - 135)	121.3 ± 10.4	(95 - 140)	*n.s.*
Zone 2	123.2 ± 9.1	(95 - 140)	120.6 ± 11.2	(100 - 140)	*n.s.*
Zone 3	123.4 ± 9.3	(95 - 140)	119.0 ± 11.0	(100 - 135)	*0.038*
Zone 4	124.7 ± 8.6	(100 - 140)	121.0 ± 10.3	(95 - 140)	*0.034*

[1] Between under-sized patients and over-sized patients (unilateral Mann-Whitney test)

Table 6: Effect of size variation in each zone on the increase in pain score and KOOS score

	Under-sized		Over-sized		
	Mean ± SD	(min - max)	Mean ± SD	(min - max)	***p values*** [1]
Gain on pain score					
Zone 1	40.1 ± 20.0	(-11.1 - 83.3)	30.2 ± 18.1	(-13.9 - 75.0)	*0.005*
Zone 2	35.2 ± 19.8	(-11.1 - 83.3)	29.5 ± 17.6	(-13.9 - 75.0)	*n.s.*
Zone 3	34.8 ± 19.4	(-13.9 - 83.3)	29.1 ± 18.3	(-5.6 - 75.0)	*n.s.*
Zone 4	37.1 ± 21.7	(-5.6 - 83.3)	31.3 ± 17.4	(-13.9 - 75.0)	*n.s.*
Gain on KOOS score					
Zone 1	33.1 ± 18.9	(-4.9 - 68.3)	26.6 ± 14.8	(-16.0 - 61.2)	*n.s.*
Zone 2	30.3 ± 16.8	(-6.4 - 68.3)	25.1 ± 15.2	(-16.0 - 54.1)	*n.s.*
Zone 3	30.0 ± 16.8	(-16.0 - 68.3)	24.5 ± 14.8	(-5.9 - 61.9)	*0.032*
Zone 4	31.3 ± 18.5	(-5.9 - 68.3)	27.2 ± 15.0	(-16.0 - 59.6)	*n.s.*

[1] Between under-sized patients and over-sized patients (unilateral Mann-Whitney test)

The increase in the pain score was 43±21 in the group with no overhang in any zone (22 patients) and 31±19 in the group with overhang in each of the four zones studied (16 patients) (p=0.033). For the KOOS score, this gain was 36±18 and 25±13 respectively (p=0.032). Mean flexion was 127°±7 in patients who presented no oversized zone and 121°±11 in those who were oversized in each of the four zones (ns).

Results of the linear regressions demonstrated less improvement in the pain score and decreased knee flexion with oversizing. This relationship was significant for the pain score in zone 1 (p=0.004), zone 2 (p=0.003) and zone 4 (p=0.012) (Figure 3). For knee flexion, it was significant in zones 2 (p=0.022) and zone 3 (p=0.010) (Figure 4). Globally, no nonlinear relationship was found and no threshold was observed.

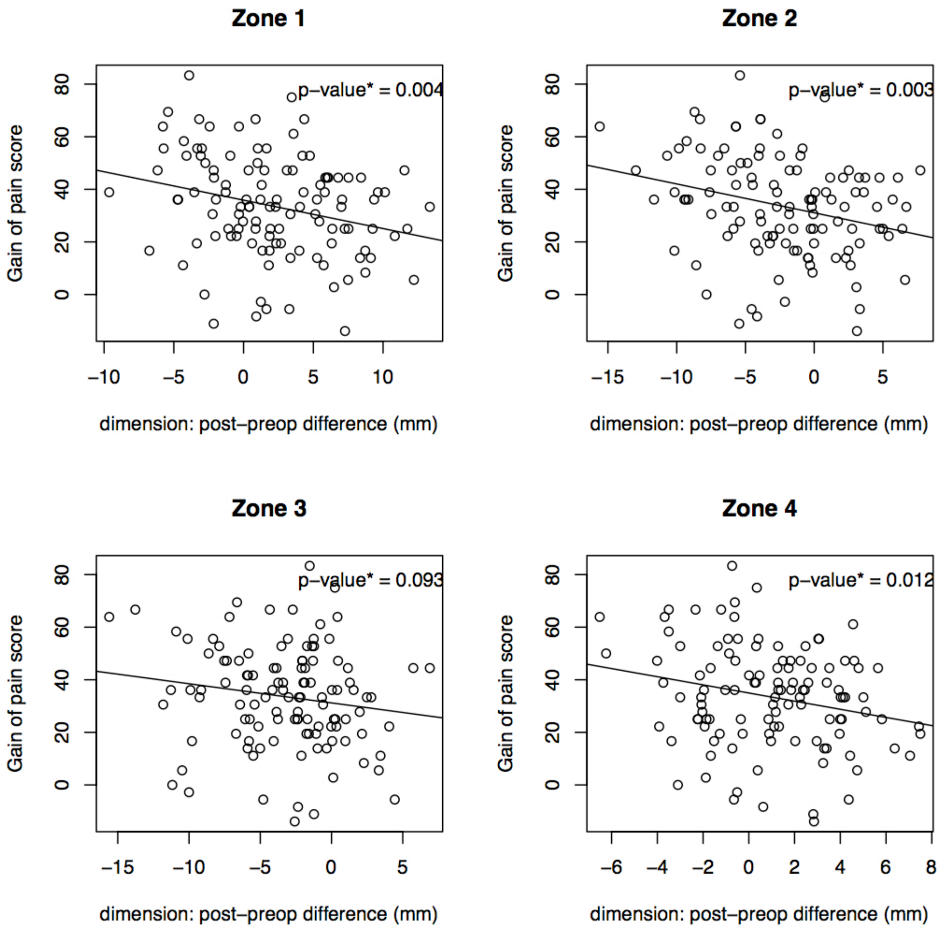

Figure 3: These figures represent the increase in the pain score (Y axis) in relation to the size variation (X axis) for the four zones studied. No threshold value was found on these curves.

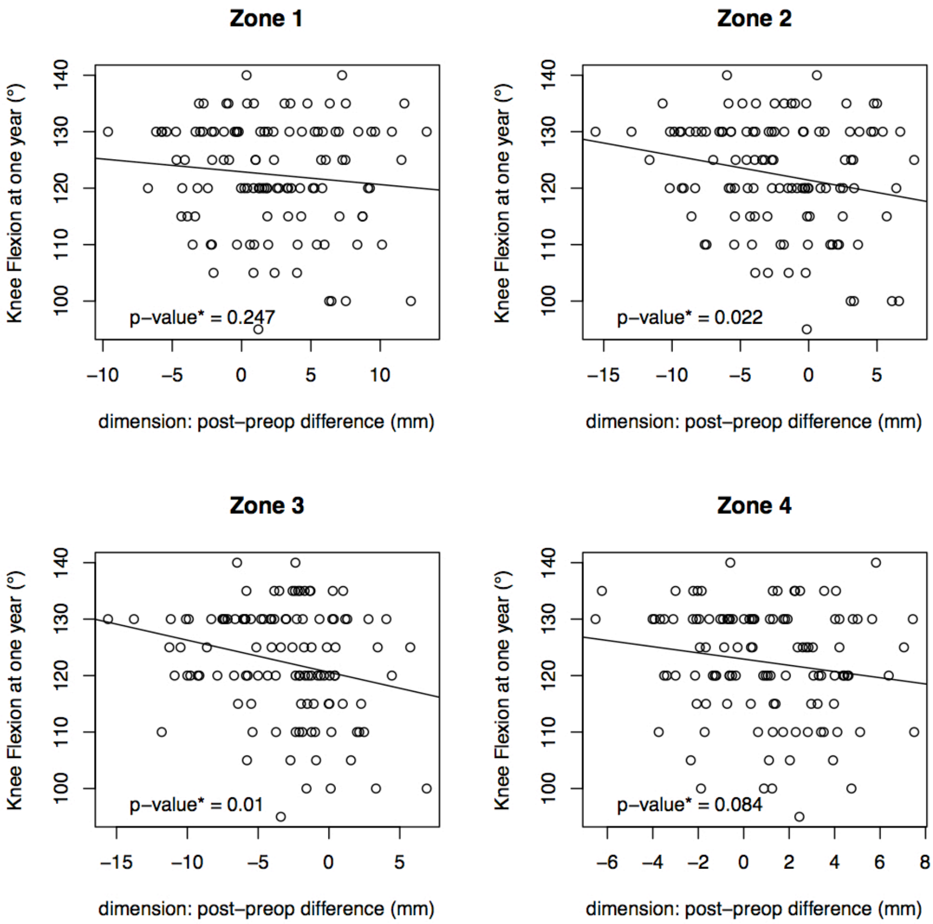

Figure 4: These figures show the flexion angle (Y axis) in relationship to the size variation (X axis) for the four zones studied. No threshold value was found on these curves.

Using a structural equation model, the two latent variables «prosthetic fit» and «post-operative outcome» were found to be negatively correlated (r=-0.26 p= 0.005) (Figure 5). When the value of the prosthetic fit was high (i.e. oversizing), the value of the postoperative outcome variable was low (i.e. a less favorable outcome).

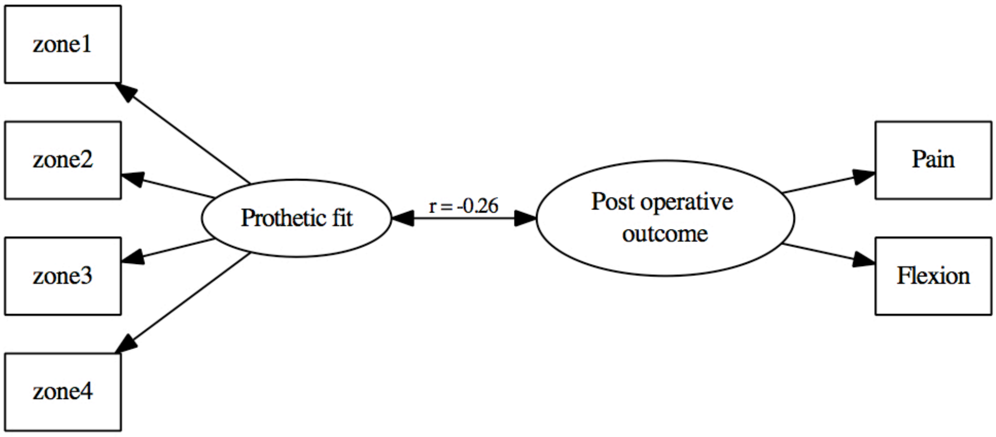

Figure 5: In the Latent Class Analysis, the first latent variable was defined as the « prosthetic fit ». It was obtained with the structural equation model from the measured variation of size in the four defined zones. The second latent variable was defined as the « post-operative outcome ». It was obtained with the structural equation model from the postoperative pain score and the MPF. The relationship between the two latent variables was explored through a Spearman correlation. In this structural equation model, the rectangles represent the observed variables while the circles represent the latent variables. The two latent variables, «prosthetic fit» and «post-operative outcome», were found to be negatively correlated (r=-0.26 with a p= 0.005).

Discussion

The most important findings of the present study were that mediolateral oversizing encountered with commonly used implants was particularly frequent, particularly in women and that oversizing, whether in the femoral or tibial component, appears to lead to an increase in the rate of residual pain, poorer knee flexion, and a decreased overall functional result.

The strength of this study resides in the use of CT measurements, which are more precise than intraoperative measurements as described by Mahoney et al.[9]. Such precision allows quantifying both under- and oversizing in millimetric increments. In addition, the administration of a validated questionnaire filled out by patients at home, prevented investigator bias. Finally, The latent class analysis permitted to reinforce the global result indicating a correlation between sizing and functional outcome.

Certain limitations of this study should be noted. First, given that only a single implant was assessed, the observations made may not necessarily apply to other prostheses, even if the aspect ratio of the design used is close to that of other, more widely utilized implants (see Appendix). Second, the study was largely retrospective in nature, even if data were obtained from a prospectively followed series. Third, the exclusion of patients due to inadequate CT scans may have introduced selection bias. Similarly, the exclusion of patients that did not answer certain questions of the KOOS might introduce similar bias. Fourth, the study purposely only assessed the mediolateral dimensions given that the anteroposterior size variations influence the ligament balance and depend also on femoral rotation[21-23]. Finally, the measurements did not analyze separately medial or lateral overhang. It is possible that medial and lateral overhang have different clinical consequences.

An attempt to precisely match implants with the bony contours of the knee is sought during TKA. The consequences of poor fitting have previously been analyzed in the anteroposterior dimension: femoral oversizing can cause pain or stiffness[24, 25] and undersizing can lead to laxity[19, 26, 27], limitation of flexion[28], or anterior cortical notching[29-32]. Few studies have assessed the consequences of mediolateral over- or undersizing[9]. The objective of the present study was to analyze the effect of mediolateral over- or undersizing of either the femoral or tibial component on function, residual pain, and flexion of the knee.

For each outcome criteria and each zone analyzed individually, the influence of sizing appeared to be moderate in our series. Indeed, when considering all zones, the maximal gains observed for pain score and KOOS score between undersized and oversized patients were 10 units and 6.5 units respectively and the difference regarding knee flexion at one year between these two groups did not exceed 4.5° (table 5 and 6). However, oversizing occurred generally in multiple zones and outcomes were significantly lower in patients with multiple oversizing. Also, the latent class analysis showed a strong association between the global prosthesis oversizing and the global clinical outcome. Our results confirm the work of Mahoney et al., who observed a twofold-increased risk of residual pain in cases of overhang of the femoral component greater than 3 mm[9]. In our series, we did not observe such a strong relation but our definition of oversizing was a pre post-operative difference greater than 0mm. For unicompartmental medial implants, Clarius et al. reported medial tibial overhang greater than 2 mm in 45% of the cases, but did not find a correlation with residual pain or the final functional result[33].

This study shows a surprisingly high rate of oversizing although non-oversizing was a priority during implantation. This can be explained firstly by the design of the implant, which is generally oversized in zone 1 but undersized in zones 2 and 3, secondly by the surgical technique; With the posterior referencing technique used in this series, the surgeon was sometimes obliged to accept an oversized implant in the ML dimension in order to avoid notching on the anterior cortex. Lastly, the limitation in the modularity, (ie femur size n cannot be used with a tibia size n-1 in the fixed bearing version of that prosthesis), forced sometimes the surgeon to make a compromise in the ideal sizing. However, it is interesting to note that Mahoney et al, reports similar findings, 76% of his patients having an overhang >0mm in at least one zone and 40% of men and 68% of women having an overhang ≥3mm in at least one zone. Optimal sizing of the tibial component can also be challenging with "standard" implants due to the asymmetry of the native tibial plateaus, to the rotational landmark used in this series (alignment with the ATT)[2] and to the lack of modularity pushing the surgeon to use oversized tibia in order to match the femoral size. The popliteal tendon, semimembranous, and medialcollateral ligament are few anatomical structures, which may cause pain and decreased ROM with oversized tibial implants in the ML plane.

In the present series, preoperative knee flexion and pain scores were lower in females, which is consistent with data from other studies[11, 34-37]. One year after surgery, the pain score, the KOOS score and knee flexion were still significantly lower in females compared to males and the increase in KOOS score was significantly higher in males. These data suggest that the results of TKA are worse in females, almost at one year follow-up, which confirms results reported by Ritter et al.[38] and Singh et al.[13]. However similar results between male and females have been also reported in other studies[34, 35, 39-44] and this led some authors to challenge the principle of designing more narrow prostheses[1, 11, 12, 45]. Variations of the geometry of both the femur and tibia have been described and have been related to several factors including patient gender[1, 3, 11, 46-51] but also morphotype[1] and ethnicity[52].

Surprisingly, the influence of size variation on clinical results was consistently linear and we observed no threshold effect. We therefore cannot determine an ideal implant size based upon the data, but can state the importance of not oversizing the components. Implant undersizing could theoretically be harmful by leaving an uncovered cancellous bone surface, were friction of the soft tissues on the bone ridges can cause pain[3]. Finally, the use of implants that are too small can be also a source of knee instability[14, 19, 26]. We did not demonstrate a negative effect of undersized implants on clinical outcomes. In fact, if anything it seemed to have a beneficial effect. This observation can perhaps be explained by our definition of under/over-sizing, taking into account the ridge of the CT slice used. Due to the design of the borders of the femoral components, a normo-sizing according to our definition can be in fact an oversizing. Optimal sizing should be probably better analyze through volume imaging than surface imaging. This point warrants further investigation, but may have possible consequences on the design of these knee implants.

Conclusion

This study confirms that mediolateral oversizing is a factor that may predict poor results in TKA. The findings also suggest that it is difficult to obtain optimal fit between the implant and bone in a large number of patients. The clinical consequences of this study are that surgeons should pay attention not to oversize implants during implantation and that oversizing should be ruled out in case of so called unexplained pain.

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5. Oversizing the tibial component in TKAs: incidence, consequences and risk factors

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Abstract

Purpose: The incidence of anterior-posterior overhang of the tibial component after TKA and it's effect on clinical outcome were investigated and the morphometric characteristics of the knees in which tibial baseplates were oversized were identified.

Method: One hundred and fourteen consecutive TKA were retrospectively assessed. The dimensions of the tibia were measured on a preoperative CT scan and were compared with those of the implanted tibial component. We analyzed the effect of anteroposterior and mediolateral size variations on clinical outcomes one year after surgery.

Results: An anteroposterior overhang was observed in 87% of cases on the lateral plateau, in 88% on the central plateau and in 25% on the medial tibial plateau. The mean post–pre operative size differences were 3.2± 2.7mm, 2.8±2.7mm and -1.6 ±2.3mm respectively. (positive value means oversizing). A mediolateral overhang of the tibial component was found in 61% of the patients. Oversizing was significantly greater and more frequent in females. Patients oversized in the anteroposterior dimension had lower post-operative pain scores. Patients with mediolateral oversizing had decreased flexion one year after surgery. Anteroposterior over-sizing was observed more frequently in patients with asymmetric tibial plateaus while mediolateral oversizing was observed more frequently in patients with small tibias.

Conclusions: This study demonstrates that the incidence of oversized tibial plateau components is surprisingly high and that functional outcomes are lower in the case of mediolateral or anteroposterior oversizing. The risk of oversizing could be predicted as it occurs predominantly in patients with asymmetric proximal tibia and/or small tibia.

Introduction

Residual pain after Total Knee Arthroplasty (TKA) is still a frequent occurence and is a major source of dissatisfaction for patients[1-8]. Oversized implants can generate residual pain after TKA due to impingement on the soft tissues surrounding the knee and to overstuffing of the knee envelope[9-13]. On the femur, high rates of up to 66% to 76% of oversized components have been reported and their responsibility in pain, stiffness and poor functional outcomes have been clearly identified[12, 14]. Consequently several manufacturers have included narrower femoral component versions to their size range, termed 'gender specific', in order to improve bone-implant fit[15-18].

On the tibia, mediolateral oversizing has proved to be a source of loss of flexion and residual pain[9, 14] but to our knowledge no study has investigated specifically the consequences of oversizing the tibial component in the antero-posterior dimension, even though several soft-tissue structures are particularly vulnerable to impingement, namely, the Patellar Tendon[19], the Iliotibial Band[20], the Popliteus Tendon[21-23] and the capsule[12]. The asymmetry and the variability of the tibial plateau aspect-ratio can also create difficulties to obtain simultaneously a good rotational alignment with an optimal bone coverage and therefore can contribute to oversizing of the tibial component[24-30]. In recent decades manufacturers have paid less attention to tibial component design than to femoral design and despite some authors demonstrating potential advantages of asymmetric tibial baseplates[28, 30-32], most manufacturers offer symmetric tibial components.

The objectives of the present study were to (i) Investigate the incidence of anterior-posterior overhang of the tibial component after TKA, (ii) to assess whether it influences the clinical outcomes of residual knee pain, function and flexion and lastly (iii) to identify the morphometric characteristics of the knees in which tibial baseplates were oversized.

Our hypotheses were that tibia oversizing was more frequent in the anterior-posterior dimension than in the medial lateral dimension and that it compromises outcomes.

Materials and Methods

Patients

This study was conducted on a cohort of patients in which we previously analyzed the incidence and the clinical consequences of mediolateral oversizing in TKA[14]. This series of 114 knees (64 females and 50 males) in 112 consecutive active patients that underwent primary TKA between January 2008 and June 2009 by the senior surgeon (MB) was retrospectively analyzed. A computed tomography (CT) scan is performed as part of a routine preoperative planning for TKA at our institution (Centre Orthopédique Santy- Lyon)[24]. The series had excluded patients with previous surgery or trauma or with an unclear CT scan due to artifacts from surrounding metal or contrast agent. The indication for TKA was medial compartment osteoarthritis in 80 knees, lateral compartment osteoarthritis in 16 knees, bi-compartmental osteoarthritis in 8 knees, patellofemoral osteoarthritis in 6 knees, and spontaneous osteonecrosis of the medial femoral condyle in 4 knees. On the preoperative long leg radiographs, 80 knees had a varus alignment with a femorotibial angle (FTA) less than 180° and 27 knees had a valgus alignment with a femorotibial angle (FTA) greater than 180°. Mean age of the patients was 72±7 years (range; 56 to 85), mean weight was 81±15 kg (range; 45 to 125) and mean height was 168±10 cm (range; 144 to 194).

Morphologic characteristics of the tibia: A 64-slice multidetector scanner (Siemens® Sensation, Munich, Germany) was used for CT scanning. All measurements were made in mm, using OsiriX®software (Pixmeo SARL, Bernex, Switzerland). The measurements were taken at the level of the tibial cut made during the operation, which was documented in the surgical report, generally 9mm distal to the most proximal point of the healthy plateau. Our previously described methodology was followed[24]. The mediolateral (ML) dimension of the tibial plateau was measured along the transverse axis of the tibia. The anteroposterior dimensions were measured at three levels: middle of the tibial plateau (AP) and then at the middle of the medial (APM) and lateral (APL) tibial plateau (Figure 1). The medio-lateral width/antero-posterior height ratio, or “aspect-ratio” (ML/AP) characterized the “ elliptic” or “rounded” shape of the tibia. The AP-medial/AP-lateral, or “symmetry-ratio”, (APM/APL) defines whether the tibial plateau was symmetric or asymmetric[24] (Figure 2). Dimensions were measured in millimeters, with one decimal. For each dimension, the cortex was included in the measurement. A special attention was paid not to include osteophytes in the measurements. To assess the accuracy of the measurements we blindly repeated the measurements on twenty sets of CT scans. A high level of intra and inter-observer reliability with errors of the mean always less than 1.5mm was found.

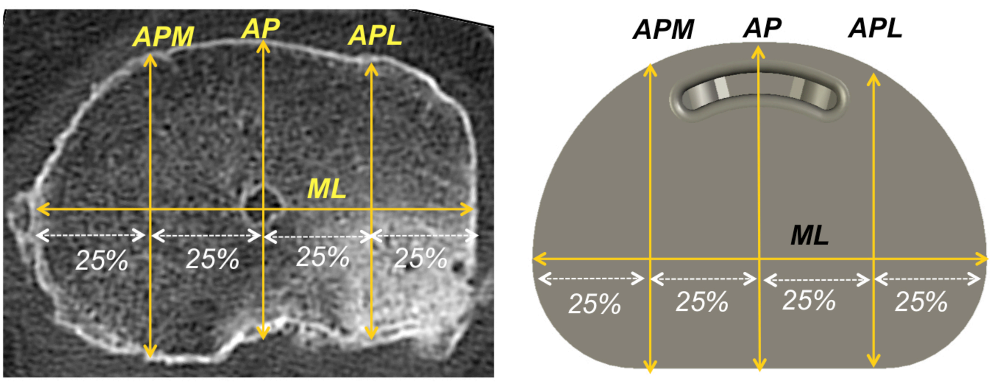

Figure 1: Measurements of the ML, AP, APM and APL dimensions done on the CT scan with the corresponding dimensions of the implanted tibial component.

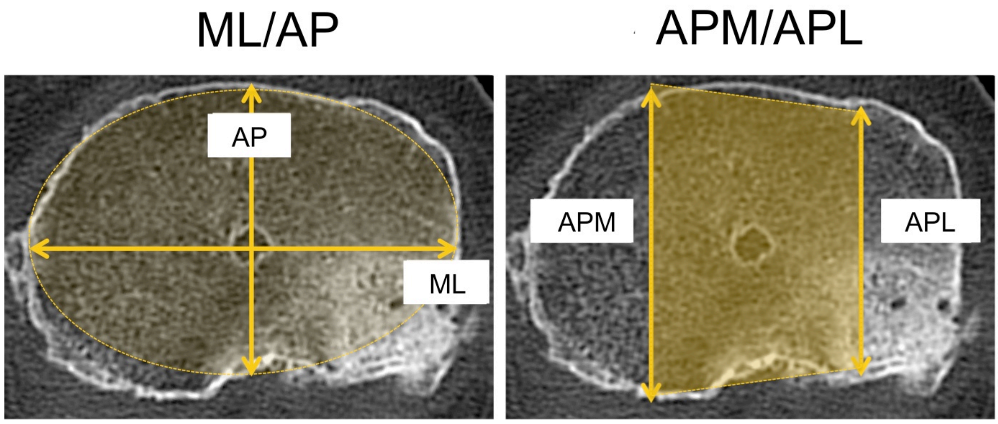

Figure 2: The "aspect-ratio" (ML/AP) characterized the "elliptic" or "rounded" shape of the tibia. The "symmetry-ratio", (APM/APL) defines whether the tibial plateau was symmetric or asymmetric

Surgical technique

All patients received a posterior, stabilized implant with a fixed, tibial tray (HLS-Noetos, Tornier SA, Montbonnot, France, FDA approved device), which included six sizes (size 1 to size 6) and whose femoral and tibia aspect-ratio was close to other currently used implants[24]. The tibia was cut first, followed by the femur with a posterior reference technique. The tibial and femoral cuts were orthogonal to the mechanical axis so as to obtain a 180° axis. Rotation of the tibial component was aligned with respect to the center of the anterior tibial tuberosity (ATT). The size of the femoral component was determined based on the instrumentation so as to prevent any notch from being created along the anterior femoral cortex. The size of the tibial component was adapted to the size of the femoral component and adjusted to match the cortical contours of the tibial cut. Mean dimensions were size 3 both on the tibia and on the femur (size 2 for females and size 4 for males). Tibial and femoral sizes were identical in 102 patients, the tibial component was one size greater than the femur in twelve patients and no patients received a smaller tibia than the femur (option was not recommended by the manufacturer). All the components were cemented (CMW3, DePuy, Warsaw, IN, USA).

Quantification of oversizing: We compared the dimensions measured on the preoperative CT scan to the corresponding dimensions of the implanted component, provided by the manufacturer. The difference between the preoperative and postoperative dimensions ("size discrepancy") was deemed positive in cases of implant oversizing and negative in cases of undersizing. For each dimension, we defined the group "oversized patients" as patients where the difference was strictly greater than 0 mm, which meant a prosthetic overhang. The group "normosized" included patients were the size variation was equal or inferior to zero. We compared the morphometric features of the tibial plateaus in patients in whom the tibial component had been oversized, to the knees where it was normosized.

Evaluation of outcomes: Before surgery, each patient completed a KOOS functional assessment self-questionnaire at home in its validated French version[33]. After surgery, the patient completed a new KOOS self-questionnaire at home one year after the TKA. The senior rehabilitation physician, who was blinded to this study, conducted a follow-up visit one year after surgery. Maximum passive flexion (MPF) of the knee was measured at this time using a goniometer on the patient seated at the end of the examination table[34]. All patients signed a written informed consent form and the institution ethics committee authorized the study (Centre Orthopédique Santy-Lyon, N° 201407).

Statistical analysis

The difference of oversizing between men and women was tested using a Student T test. The effect of size variation (under- or oversizing) in the four zones defined was analyzed with respect to pain, function, and flexion one year after implantation. To limit the risk of error related to multiplicity of statistical tests, only three main variables were studied: pain was assessed using the pain subscore (P) of the KOOS score, overall function by the overall

KOOS score, and flexion by the angle of MPF[33, 34]. For each patient, both the postoperative score and the score improvement were studied. For each zone studied, two groups were compared: the oversized prosthesis group versus the normal or undersized prosthesis group using the unilateral, nonparametric Mann-Whitney test. The mean of each ratio between males and females was compared using a Mann-Whitney test. Correlation coefficients of Spearman were calculated between ratios and between ratios and age, BMI and FTA, their values were compared to zero. Considering the tibial APL oversizing, the mean of each ratio was compared between oversized patients and normo- or undersized patients using a Mann-Whitney test.

To evaluate the risk factors associated with oversizing an ascendant linear regression was used. The explanatory variables were; the two ratios, the gender, the dichotomized FTA variable (using a threshold of 180°) and the mediolateral dimension of the tibia. Only the mediolateral and the lateral anteroposterior oversizings were studied in the model. Values of ratios were normalized. As some of the explanatory variables were correlated, the variance inflation factor (VIF) was calculated for each of the variables in order to evaluate the impact of the multicollinearity on the variance of the corresponding estimated coefficient. It was always inferior to 5 meaning that the effect of multicollinearity on the estimations could be considered as negligible.

No control for multiple testing was applied. Each test was considered as significant if the p-value was inferior to 0.05. Analyses were performed using R software.

Results

An anteroposterior overhang was observed on the lateral plateau in 87% of the patients (99 knees), 92% in females and 80% in males. The mean pre-post operative size difference in this area was 3.2± 2.7mm (range; -4.7 to 10.3mm) (Table 1 and Figure 3). On the central tibial plateau, an oversizing was observed in 88% of the patients (100 knees), 92% in females and 82% in males. The mean pre-post operative size variation was 2.8±2.7mm (range; -3.4 to 12.1). On the medial tibial plateau only 25% of the patients were oversized (29 knees) in the anteroposterior dimension and the mean pre/post operative size variation was -1.6 ±2.3mm (range; -8.4 to 3.3 mm). A mediolateral overhang of the tibial component was found in 61% of the patients (70 knees), 81% for females and 40% for males. The mean mediolateral pre-post operative size difference was 0.9±2.9mm (range, -6.6mm to 7.6 mm), 1.9±2.7mm for females (range, -6.5mm to 7.5 mm) and -0.3±2.7mm for males (range, -6.2mm to 6.4 mm). For all the dimensions studied excepted the APL dimension, oversizing was significantly greater in females.

Table 1: Difference between preoperative dimensions (CT scan) and implant dimensions (mm)[1] on the four studied zones

	Series		**Men**		**Women**		
	Mean ± SD	(min - max)	Mean ± SD	(min - max)	Mean ± SD	(min - max)	***p values*[2]**
APL	3.2 ± 2.7	(-4.7 - 10.3)	3.0 ± 2.8	(-2.5 - 10.3)	3.3 ± 2.6	(-4.7 - 8.0)	*n.s.*
APM	-1.6 ± 2.3	(-8.4 - 3.3)	-2.4 ± 2.2	(-8.4 - 1.2)	-1.0 ± 2.1	(-6.3 - 3.3)	*<0.001*
AP	2.8 ± 2.7	(-3.4 - 12.1)	2.0 ± 2.8	(-3.4 - 12.1)	3.4 ± 2.4	(-3.0 - 8.8)	*<0.005*
ML	0.9 ± 2.9	(-6.7 - 7.6)	-0.3 ± 2.7	(-6.2 - 6.4)	1.9 ± 2.7	(-6.5 - 7.5)	*<0.001*

[1] Negative value means undersizing
[2] Between women and men (Student T test)

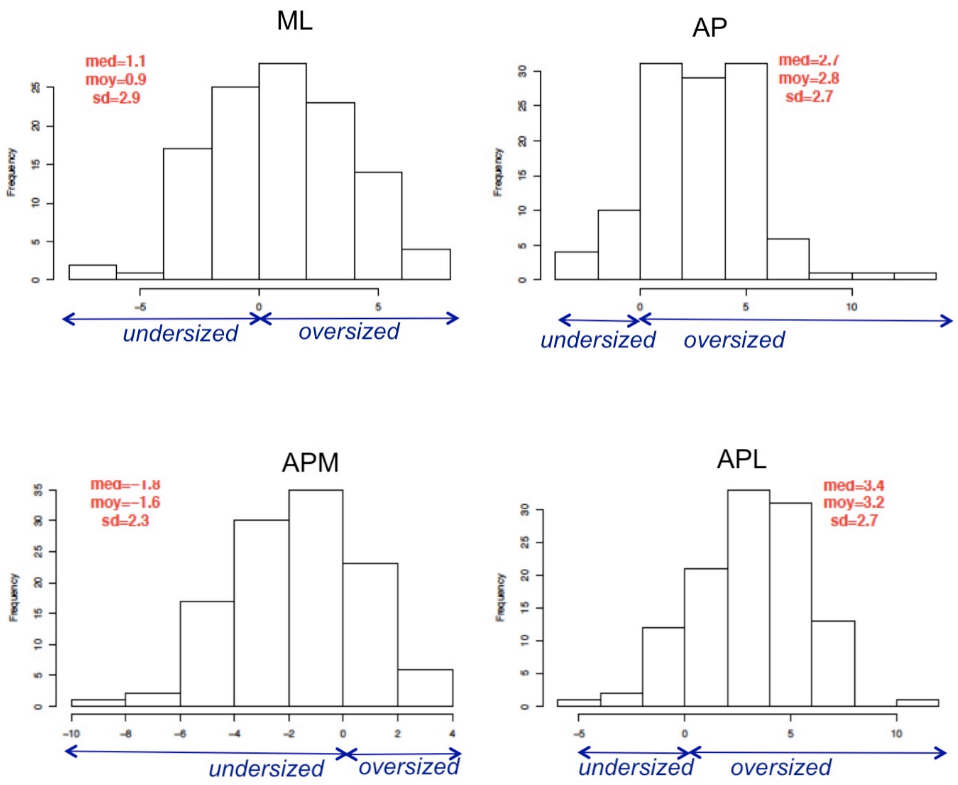

Figure 3: These histograms represent the distribution of the size variation in the four zones studied. The X axis represents the postoperative-preoperative size difference in mm. A positive value means an oversizing.

Pre and postoperative data of the series are mentioned in Tables 2 and 3. Oversized patients in the anteroposterior dimension in any of the three studied areas had lower post-operative scores. However, the comparison with normosized patients was only significant for the central tibia area: p=0.012 for pain score and p=0.006 for the gain of pain score and for the mediolateral area for the flexion (p=0.024) (Table 4 and 5).

Table 2: Preoperative scores

	Series		**Men**		**Women**		
	Mean ± SD	(min - max)	Mean ± SD	(min - max)	Mean ± SD	(min - max)	***p values*** [1]
Pain score	45 ± 15	(0 - 94)	49 ± 15	(8 - 94)	42 ± 15	(0 - 69)	*0.030*
KOOS score	36 ± 11	(6 - 81)	38 ± 12	(12 - 81)	34 ± 11	(6 - 55)	*n.s.*
Flexion (°)	105 ± 10	(60 - 125)	107 ± 8	(60 - 125)	102 ± 10	(60 - 120)	*0.040*
FTA (°)	176 ± 5	(160 - 194)	175 ± 5	(165 - 186)	177 ± 6	(160 - 194)	*0.003*

[1] Between women and men (Student T test)
Abbreviation: FTA, Femorotibial angle measured on the long leg X-Rays from the mediazl side (<180° means varus deformity)

Table 3: Postoperative scores

	Series		Men		Women		
	Mean ± SD	(min - max)	Mean ± SD	(min - max)	Mean ± SD	(min - max)	*p values* [1]
Pain score	79 ± 18	(28 - 100)	84 ± 17	(28 - 100)	75 ± 18	(36 - 100)	*0.005*
KOOS score	64 ± 17	(24 - 98)	71 ± 17	(31 - 98)	59 ± 16	(24 - 97)	*<0.001*
Flexion (˚)	122 ± 10	(95 - 140)	125 ± 8	(100 - 140)	121 ± 11	(95 - 140)	*0.038*
FTA (˚)	178 ± 3	(172 - 186)	177 ± 3	(172 - 183)	179 ± 3	(173 - 190)	*0.028*
Increase in Pain score	34 ± 19	(-14 - 83)	35 ± 19	(-11 - 75)	32 ± 19	(-14 - 83)	*n.s.*
Increase in KOOS score	29 ± 16	(-16 - 68)	33 ± 17	(-6 - 68)	25 ± 15	(-16 - 57)	*0.018*

[1] Between women and men (Student T test)
Abbreviation: FTA, Femorotibial angle measured on the long leg X-Rays from the mediazl side (<180° means varus deformity)

Table 4: Effect of size variation in each zone on postoperative pain score, KOOS score and knee flexion

	Under-sized		Over-sized		
	Mean ± SD	(min - max)	Mean ± SD	(min - max)	***p values*** [1]
Pain score					
Zone 1	84.4 ± 13.6	(56 - 100)	78.4 ± 18.3	(28 - 100)	*n.s.*
Zone 2	79.5 ± 18.1	(28 - 100)	78.2 ± 17.1	(39 - 100)	*n.s.*
Zone 3	88.8 ± 12.2	(61 - 100)	77.8 ± 18.1	(28 - 100)	*0.012*
Zone 4	81.1 ± 18.4	(36 - 100)	77.3 ± 17.8	(28 - 100)	*n.s.*
KOOS score					
Zone 1	69.4 ± 18.3	(33 - 98)	63.9 ± 17.0	(24 - 97)	*n.s.*
Zone 2	65.3 ± 16.9	(24 - 97)	62.7 ± 18.0	(25 - 98)	*n.s.*
Zone 3	72.9 ± 14.2	(54 - 98)	63.5 ± 17.3	(24 - 97)	*0.059*
Zone 4	67.7 ± 16.8	(33 - 98)	62.3 ± 17.3	(24 - 97)	*n.s.*
Knee flextion					
Zone 1	124.3 ± 10.3	(100 - 140)	122.1 ± 9.8	(95 - 140)	*n.s.*
Zone 2	122.6 ± 9.5	(100 - 140)	121.7 ± 10.9	(95 - 140)	*n.s.*
Zone 3	123.9 ± 9.2	(110 - 140)	122.2 ± 9.9	(95 - 140)	*n.s.*
Zone 4	124.7 ± 8.6	(100 - 140)	121.0 ± 10.3	(95 - 140)	*0.034*

[1] Between under-sized patients and over-sized patients (Mann-Whitney test)

Table 5: Effect of size variation in each zone on the increase in pain score and KOOS score

	Under-sized		Over-sized		
	Mean ± SD	(min - max)	Mean ± SD	(min - max)	***p values*** [1]
Gain on pain score					
APL	37.2 ± 18.6	(3 - 64)	33.0 ± 19.6	(-14.0 - 83)	*n.s.*
APM	34.1 ± 19.7	(-11 - 83)	32.1 ± 19.3	(-14.0 - 56)	*n.s.*
AP	45.5 ± 16.8	(17 - 69)	31.9 ± 19.0	(-14.0 - 83)	*0.006*
MLT	37.1 ± 21.7	(-6 - 83)	31.3 ± 17.4	(-13.9 - 75)	*n.s.*
Gain on KOOS score					
APL	30.2 ± 18.6	(-5.6 - 61.4)	28.3 ± 16.3	(-16.2 - 68.6)	*n.s.*
APM	29.1 ± 15.6	(-6.6 - 68.6)	26.9 ± 19.3	(-16.2 - 65.8)	*n.s.*
AP	35.9 ± 17.8	(6.8 - 65.8)	27.5 ± 16.2	(-16.2 - 68.6)	*0.065*
MLT	31.3 ± 18.5	(-5.9 - 68.3)	27.2 ± 15.0	(-16.0 - 59.6)	*n.s.*

[1] Between under-sized patients and over-sized patients (Mann-Whitney test)

No relation was observed between ML/AP and APM/APL ratios and gender or age, but patients with a greater BMI and patients with valgus alignment had more asymmetric tibia, i.e. greater APM/APL ratio (respectively, p = 0.002 and p = 0.018).

Anteroposterior over-sizing on the lateral tibial plateau was observed mostly in patients with asymmetric tibial plateaus. The mean APM/APL was 1.03±0.09 (range, 0.90 to 1.20) in normosized patients and 1.13±0.07 (range, 0.83 to 1.33) in oversized patients (p<0.001). Aspect ratio (ML/AP) was similar in both groups of patients (respectively 1.52±0.10 and 1.53±0.09, p=0.821) (Table 6 and Figure 4). The linear regression showed also that the main factor related with tibial APL over-sizing was the asymmetry between the medial and lateral plateaus (p<0.0001). Each increase of one standard deviation of APM/APL ratio increases the over-sizing by 1.27mm.

Table 6: Values of the ML/MP and APM/APL ratios

	ML / AP		APM / APL	
	Mean ± SD	(min - max)	Mean ± SD	(min - max)
Series	1.53 ± 0.09	(1.33 - 1.93)	1.11 ± 0.08	(0.83 - 1.33)
Men	1.54 ± 0.10	(1.4 - 1.9)	1.12 ± 0.09	(0.9 - 1.3)
Women	1.52 ± 0.07	(1.4 - 1.7)	1.11 ± 0.08	(0.8 - 1.3)
p values [1]	*n.s.*		*n.s.*	
Oversized	1.53 ± 0.09	(1.30 - 1.9)	1.13 ± 0.07	(0.80 - 1.3)
Undersized	1.52 ± 0.10	(1.40 - 1.7)	1.03 ± 0.09	(0.90 - 1.2)
p values [2]	*n.s.*		*<0.001*	

[1] Between women and men (Mann-Whitney Test)
[2] Between under-sized and over-sized (Mann-Whitney Test)

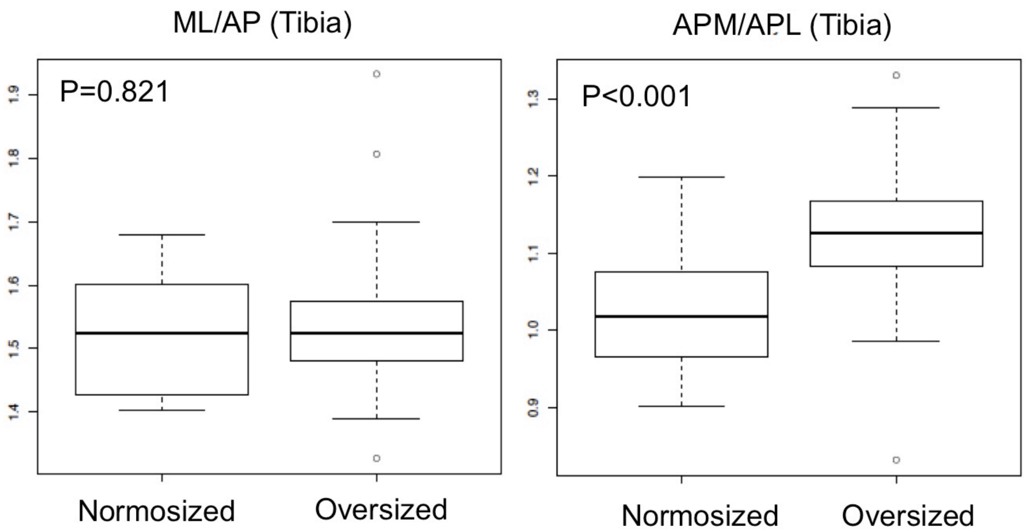

Figure 4: These boxplots represent the value of the ML/AP and APM/APL ratio in the oversized and undersized patients.

Linear regression showed that the only factor related with mediolateral oversizing was the mediolateral dimension of the tibial plateaus ($p<0.001$). The smaller the tibia was, the higher the risk of ML over-sizing was and a decrease of 5 mm in the mediolateral dimension of the tibia increased the over-sizing by 1mm.

Discussion

The most important findings of this study were (i) that the rate of oversized tibial plateau was surprisingly high, particularly in the lateral and central anteroposterior dimensions, (ii) that functional outcomes were lower in case of tibial oversizing and (iii) that the risk of oversizing could be predicted as it occurs mostly in patients with asymmetric proximal tibia and/or small tibia.

In the last two decades numerous morphometric investigations have drawn attention to the anatomic variations of the distal femur and proximal tibia and to their surgical consequences: the difficulties to rebuild the native shape of the knee and to avoid prosthetic overhang. Matching the prosthetic component with the host bone seems at first glance more challenging for the femur where anteroposterior sizing, component rotation and ligament balancing are all interrelated[12, 14]. The consequences of an inadequate femoral sizing can be severe: weakening of the anterior cortex[35] or flexion instability[36] in case of undersizing; residual pain due to soft-tissue impingement or stiffness in case of oversizing[12, 14]. At the tibia, the surgeon has apparently more flexibility and the consequences of incorrect sizing seem less catastrophic. However many factors, such as the level of the tibial cut, the femoral size and the rotational alignment of the tibia are linked with the tibial size, which increases the margin of error for the surgeon. We therefore asked: (i) What is the true incidence of tibial oversizing? (ii) Does tibial oversizing affects outcomes after TKAs'? (iii) Do we need a specific design for high-risk patients of oversizing, i.e., very asymmetric plateaus and a small tibia?

This study presents several limitations. First, only one TKA design with a fixed bearing was implanted in this series. It is unclear whether our conclusions can be extended to other implants and to mobile bearing prostheses. However, it should be noted that the ML/AP aspect ratio of the tibial baseplate used is close to other widely utilized implants[24]. Second, the patients in this series were all Caucasians and morphologic characteristics cannot be extended to Asian or African populations. Third we analyzed the global variation of size for each studied dimension but we didn't differentiate the direction – anterior or posterior and medial or lateral- of the overhang.

Diverse factors may explain why such a high rate of overhang was observed on the lateral and central plateau in this series. First, optimizing bone coverage with a symmetric tibial component is difficult in patients with asymmetric plateaus. Several authors have described the classic asymmetry of the proximal tibia - smaller lateral plateau and larger medial plateau- which make it challenging to obtain a good bone-implant fit during TKAs'. In this series, despite a mean undersizing of 1.6 mm on the medial plateau, we observed a 3.2 mm mean oversizing on the lateral plateau. Undersizing the tibial component by one size could have lead to insufficient bone coverage[37]. Ideally, tibial baseplates should replicate this asymmetry but intraoperative adjustment with asymmetric implants has proven to be difficult[26, 27, 38] and a significant proportion of patients up to 17% have symmetric plateaus or a reversed asymmetry with a lateral plateau greater than the medial one in the anteroposterior dimension[24, 26]. This reversed asymmetry was observed in 10 patients (9.8%) in this series. Recently, Mori et al.[39] analyzed the bone-implant fit in 90 Japanese patients using five different designs of tibial baseplates. Due to wide variations in the aspect-ratio of the resected tibial surface, none of the implants perfectly fit the tibia. Second, the fact that we aligned the rotation of the tibial baseplate on the ATT may be another contributing factor. Even if there is no consensus on the best rotational landmarks on the tibia, there is a general agreement to externally rotate the implant with respect to the posterior tibial margin. The surgeon is then frequently obliged to accept a compromise, i.e., undersizing on the medial plateau and/or overhanging on the postero lateral plateau (Figure 5). In a study of 20 cadaver knees, Lemaire et al.[27] reported a mean differential angle of 9.8° between position for optimum bone coverage and alignment with the ATT for the Insall-Burnstein II prosthesis. Recently, Martin et al.[28] compared four commercially available tibial baseplates, two symmetric and two asymmetric, and observed that it was easier to satisfy both rotational alignment and optimal bone coverage with asymmetric implants[28]. Third, another technical issue is the possibility to mismatch the femoral and tibial sizes. The implant used in this series had a fixed-bearing baseplate, which allows only a limited mismatch (femur size n cannot be used with a tibia size n-1). Therefore, in some patients the use of an excessively large tibial component was imposed by the choice of the femoral size. Berend et al.[40] reported the same difficulties with the AGC prosthesis (Biomet Inc, Warsaw, IN) and observed higher stress on the polyethylene and early tibial loosening when using a tibia smaller than the femur. Some other designs allowing a greater femur/tibia mismatch could theoretically improve that issue but engineering limitations exist due to the resistance of the polyethylene[41, 42]. Rotating platforms, which enable surgeons to freely mismatch the tibial and femoral sizes, may also be another option to address this sizing challenge. However, long-term clinical evaluation failed to demonstrate any difference in outcomes between mobile and fixed bearing TKAs[43].

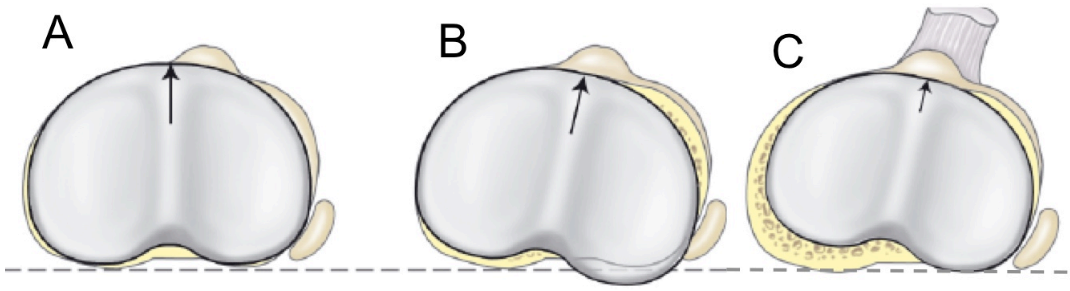

Figure 5: Illustration of the difficulties encountered while positionning the tibial baseplate in TKA. This well-sized symmetric tibial plateau is aligned on the posterior tibial margin (A). If the surgeon tries to align the tibia with ATT, a postero-lateral overhang appears with a postero-medial and anterolateral loss of coverage (B). To prevent posterolateral overhang, the surgeon can undersize the tibial component but this option decreases medio lateral bone coverage and can be source of mismatch in sizes between femur and tibia (C).

The consequences of oversizing the tibial component in TKA have been poorly analyzed in the literature. Some authors reported higher rates of pain in the case of mediolateral tibial overhang both in TKAs' and UKAs'[9, 14, 44-46]. Anteroposterior oversizing of the femur has proven to be a source of pain [10, 13] but to our knowledge no studies investigated the influence of anteroposterior oversizing on the tibia. Mediolateral tibial overhang can cause soft tissue impingement, particularly with the medial collateral ligament (MCL) on the medial side, which is very close to the implant and with the iliotibial band on the lateral side at the level of its Gerdy's insertion[20]. Anterior overhang can lead to painful impingement with the Patellar tendon during deep knee flexion[19], posterolateral overhang can damage the popliteus tendon, which is in very close relation with the prosthetic component both on the femur and the tibia[21-23] and anterolateral overhang can cause impingement with the iliotibial band[20].

The clinical relevance of this study is that surgeons should be aware of the clinical consequences of posterior tibial overhang, particularly in the posterolateral corner. Surgeons should keep a watchful eye on this area, which is poorly visualized intraoperatively.

Conclusion

The present work confirms that tibial overhang may compromise the functional outcomes in TKA. The high frequency of tibial overhang is multifactorial, due to intraoperative factors, design limitations and morphologic characteristics; patients with asymmetric tibial plateaus and patients with small sizes, have a higher risk. Surgeons must pay a particular attention to avoid posterolateral overhang and several design aspects such as the aspect ratio, the tibial asymmetry and the femur-tibia conformity should be reanalyzed.

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Section II

Anatomic variability of the bony surfaces

6. Is the anterior tibial tuberosity a reliable rotational landmark for tibial component in TKA

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Abstract

To analyze the morphology of the tibial plateau, we studied 100 CT scans of arthritic knees and measured the ML and AP dimensions as well as their aspect ratio using 3 reference axes of rotation: TransEpicondylar Axis (TEA), Posterior Tibial Margin (PTM) and Anterior Tibial Tuberosity axis (ATT). Relative to the TEA, the PTM was internally rotated by 1.6°±5.1° and the ATT externally rotated by 14.8°±7.2. The AP and ML dimensions and aspect ratio differ significantly when the reference axis was ATT compared with PTM or TEA and variations were greater while using ATT axis. Our data demonstrate (i) that design of the tibial component restricts the choice of rotational alignment and (ii) that ATT is not a reliable landmark for rotation of tibial component.

Introduction

Correct positioning of the tibial component in total knee arthroplasty (TKA) requires satisfaction of two criteria simultaneously: First, implant rotation must be meticulously adjusted to ensure optimal knee kinematics and patellar tracking[1-7]. Second, prosthetic coverage of the resected tibial surface should be optimized to ensure uniform load transfer and optimal implant fixation and stability, without prosthetic overhang[8-14].

There is little or no consensus in the literature about the ideal rotational alignment of the tibial component in TKA. A number of studies reported rotation with reference to the posterior tibial margin (PTM)[15], or relative to bony landmarks such as the medial margin of the anterior tibial tuberosity (ATT)[11], or the midsulcus of the tibial spines[16]. Other authors recommended rotation relative to distal reference axes of the foot or ankle[15, 17, 18]. Aligning the tibial tray parallel to the femoral transepicondylar axis (TEA) is also a logical choice if the femoral component is already aligned to this axis. This can be achieved either intraoperatively by aligning the trial tibial tray with the implanted femoral component[2, 19], or preoperatively using computed tomography (CT) scans to prescribe the necessary rotation[20, 21].

Some studies have shown that an increased external rotation of the tibial component could improve patello-femoral tracking, suggesting alignment with the center of the ATT[2, 19, 22, 23]. In this case, however, the surgeon can be faced with a difficult compromise to satisfy both positioning criteria. Depending on its design, rotating the tibial tray to optimize patellofemoral kinematics can decrease plateau coverage, and vice versa[22].

Our hypothesis was that the design of the tibial component influences the intra-operative choice of rotational reference axis and that alignment of the tibial component with ATT requires a specific design. The aims of our study were to measure and compare the morphology of the proximal tibia using three different reference axes (TEA, PTM, and ATT) and to compare dimensions of the medial and lateral tibial plateaus and hence the perceived tibial asymmetry using the different reference axes.

Material and Methods

Patients

At our center, CT scaning of the lower limb is a part of the standard preoperative planning for TKA since 2003. The preoperative CT images enable accurate planning of implant rotation angles, notably the femoral component with respect to the transepicondylar axis[24-26]. In a retrospective study, we analyzed 100 CT scans of the lower limb performed on 100 patients planned for TKA in 2006. The preoperative planning also included frontal and lateral weight bearing X-rays of the knee, a long weight bearing X-ray of both lower limbs, with full images of both knees and hips, as well as a skyline view of both patellae. All patients had given informed consent for imaging and surgery and approval from Institutional Review Board and Ethical Committee was obtained.

All studied knees were diagnosed with stages II or III osteoarthritis [27] and received a TKA. We excluded patients with severe deformities that could cause tibial misalignment in the CT scanner: rheumatoid arthritis, history of previous knee surgery or trauma, severe osteoarthritis (stages IV and V)[27], deformity in mechanical tibiofemoral angle (mTFA) greater than 10°, and stiff knees with more than 5° loss of extension. We selected specimens to form two comparable groups: 50 females and 50 males. A total of 52 right knees and 48 left knees were available for analysis. The mean age of patients was 75.3±7.1 years (range, 52 to 86 years) for females and 74.2±8.7 years (range, 43 to 92 years) for males. The mean mTFA was 176.4°±5.6° (range, 170 to 190°).

CT scan analysis

All patients had been scanned following an identical protocol using a 64-slice multidetector scanner (Siemens® Sensation, Munich, Germany). Patients were scanned in the supine position with the knees fully extended and legs fixed in neutral rotation. The hip was scanned from the anterior inferior iliac spine to the lesser trochanter, and the knee from 50mm above the superior patellar margin to the bottom of the anterior tibial tuberosity. We used image processing software dedicated to DICOM images, OsiriX (open-source software; http://homepage.mac.com/rossetantoine/osirix), to generate three-dimensional (3-D) bone reconstructions of the CT scans[28, 29]. In this study, however, we used new software features that allow digitization of specific points on two- and three-dimensional bone surfaces and exportation of their coordinates to spreadsheets for processing[30].

For each patient, we digitized a number of points in two- and three-dimensional views. On the femur we digitized the head centre, the anterior femoral cortex immediately above the patella, the lateral and medial epicondyles, as well as the posterior condylar margins at the level of the intercondylar notch[31]. The transepicondylar axis was defined as the line connecting the sulcus of the medial epicondyle and the lateral epicondyle[3]. On the tibia we identified the transverse view corresponding to the theoretical resection level (9mm below the healthy plateau) and digitized the complete intramedullary cortical contour. At the same level, we aligned the image to the posterior tibial margin (PTM) and then digitized the most posterior points of the medial and lateral plateaus. Finally, we digitized the middle of the anterior tibial tuberosity (ATT) at the level where the patellar tendon started to detach from the tibia[21]. For each CT scan, the coordinates of digitized points were exported using OsiriX, to a comma-separated variables file, which could be manipulated in spreadsheets using Microsoft® Excel (Microsoft Corp, Redmond, WA).

Morphometric analysis

The femoral coordinate system was established with its origin at the mid-epicondylar point, and the frontal femoral plane passing through the head centre and the epicondyles. The z-axis was defined by the femoral mechanical axis intersecting the origin and the femoral head centre; the y-axis by the anteroposterior axis orthogonal to the frontal femoral plane; and the x-axis by the mediolateral axis orthogonal to the y- and z-axes. Note that in this coordinate system, the frontal (x-z) plane is established based on the femoral head centre, thus the x-axis runs close to the transepicondylar axis (TEA) but is not necessarily aligned to it.

The tibial coordinate system was established with its origin at the geometric centre of the digitized cortical contour. The spreadsheet of each knee was reproduced in three copies to enable data representation with reference to the three described axes (Figure 1): the TEA by aligning the x-axis to the epicondyles, the PTM by aligning the x-axis to the most posterior points of the medial and lateral plateaus, and ATT axis by aligning the y-axis to the line that connects the ATT to the geometric centre of the tibial plateau (ATT line) (Figure 2). In each case the angles between the three reference axes were measured. The principal dimensions measured on the theoretical resection plane of the tibia were the central AP dimension (*along* the y-axis) and the maximum ML dimension (*parallel* to the x-axis). The aspect ratio (maximum ML dimension divided by central AP dimension) was calculated as described by Hitt and Shurman[32]. The aspect ratios calculated according to our three reference axes (TEA, PTM and ATT) were compared with those of four current prosthetic systems for which manufacturers provided precise dimensions: Nexgen (Zimmer, Warsaw IN, USA), PFC (DePuy, Warsaw IN, USA), Genesis 2 (Smith & Nephew, Memphis TN, USA) and Noetos (Tornier, Montbonnot, France). We also measured the AP dimension at different levels (10%, 20% and 30% from the medio-lateral peripheries) on the medial (AP_M) and lateral (AP_L) plateaus as described by Westrich and Haas[33]. We analyzed the asymetry between the lateral and medial plateaus and the ratio between the lateral and medial anteroposterior dimensions was calculated at each level (10%, 20% and 30%).

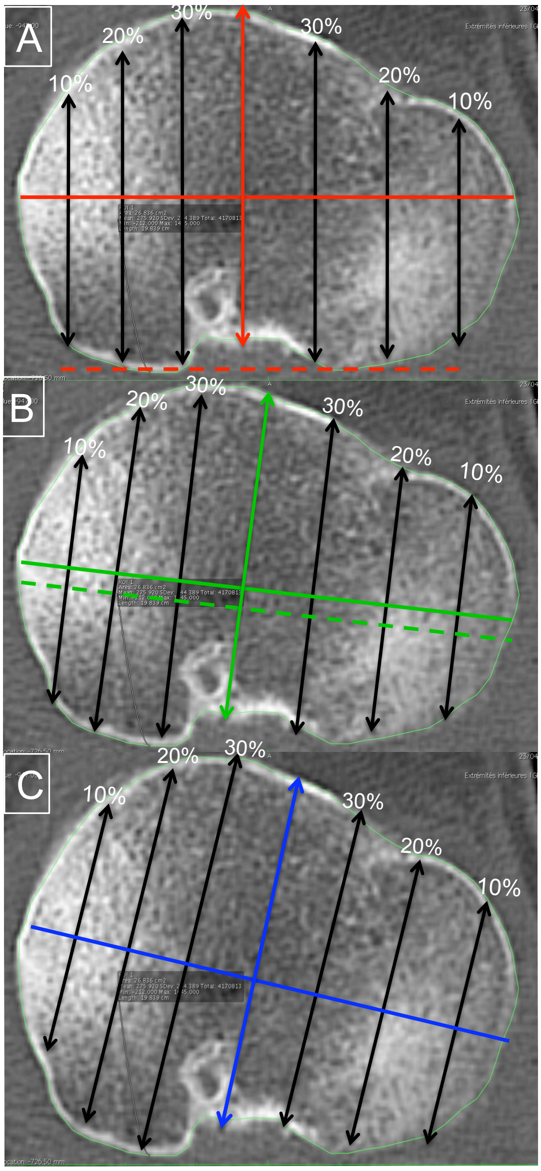

Figure 1: Morphometric analysis of the tibial plateau was based on AP and ML dimensions (colored solid lines) and the AP dimension in the different zones of the tibial plateaus as described by Westricht et al.. Measurements were done in alignment with the three reference axes: (A) Posterior tibial margin (dashed red), (B) Projected transepicondylar axis (dashed green) and (C) Anterior tibial tuberosity axis.

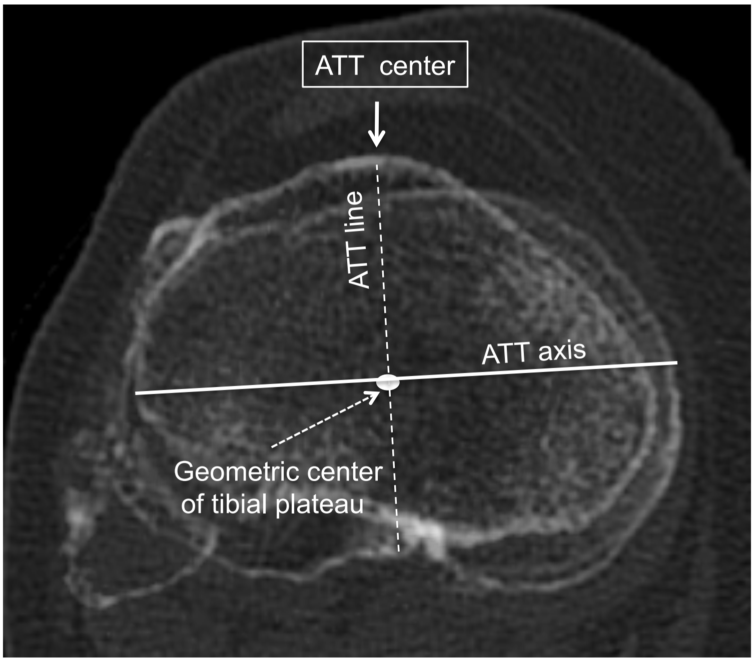

Figure 2: Illustration of determination of ATT-axis. The geometric center of the tibial plateau is localized at the theoretical resection level. The center of the ATT is localized at the level where the patellar tendon starts to detach from the tibia. After superposition of the two slices, ATT-line and AT-axis are drawn.

Statistical analysis

We conducted statistical analyses for comparison of morphometric data with age, AP and ML dimensions, aspect ratios and angles between males and females using unpaired t tests. Correlations between variables were calculated using the Pearson product moment coefficient of correlation (r). The significance level was set at 0.05. The statistical package we used was Microsoft® Excel and its statistical software (Microsoft Corp).

Results

The mean angle between the femoral mechanical axis (z-axis) and the transepicondylar axis in the frontal femoral plane was 88.5°± 2.6 (range, 82.5° to 95.3°).

The PTM was on average internally rotated with respect to the TEA (mean angle, 1.6°±5.1°; range, 12.4° external rotation to 14.5° internal rotation) with no significant difference between males and females (p=0.33). The ATT axis was on average externally rotated with respect to TEA (mean angle, 14.8°±7.2°, range, 14.6° internal rotation to 29.0° external rotation) with no significant difference between males and females (p=0.24). Only 2 out of 100 patients had an ATT axis internally rotated with respect to the TEA.

The AP and ML dimensions were almost identical when measured aligned to the TEA or PTM, but significantly different when measured aligned to the ATT axis (Table 1). Using the ATT axis, the AP dimension is greater (p<0.001) and the maximum ML dimension is smaller (p<0.001). The ML/AP aspect ratio is almost identical when the dimensions are measured with respect to the TEA or PTM (p=0.65), but the ML/AP aspect ratio is significantly lower when the dimensions are aligned to the ATT axis (p<0.0001). Moreover, the dispersion of the data is much greater when measurements are aligned with ATT axis (Figure 3). The aspect ratio was identical in males and females when the reference axis is either the TEA or PTM (p > 0.5) but was significantly greater in females (p<0.0001) when using the ATT axis as reference (Table 1).

Table 1: Principal morphometric data compared to the literature

Parameter	Author	Year	Source	Method	Reference Axis	Total (n=100) Mean ± SD	Total (n=100) (min - max)	Women (n=50) Mean ± SD	Women (n=50) (min - max)	Men (n=50) Mean ± SD	Men (n=50) (min - max)	p values
Age (yrs)	This study		France	CT scans		74.7 ± 7.8	(43 - 92)	75.3 ± 7.1	(52 - 86)	74.2 ± 8.7	(43 - 92)	*0.4895*
Tibia AP (mm)	This study		France	CT scans (n=100)	TEA	46.2 ± 4.2	(35.1 - 57.3)	43.3 ± 2.7	(35.1 - 49.2)	49.1 ± 3.3	(42.6 - 57.3)	*<0.0001*
					PTM	46.4 ± 4.1	(35.7 - 57.2)	43.5 ± 2.4	(35.7 - 47.9)	49.2 ± 3.4	(41.3 - 57.2)	*<0.0001*
					ATT	51.0 ± 8.1	(35.5 - 74.3)	45.2 ± 3.4	(35.5 - 52.4)	56.8 ± 7.2	(45.5 - 74.3)	*<0.0001*
	Kwak et al.	2007	Korea	CT scans (n=200)		45.7 ± 3.8		43.2 ± 2.3		48.2 ± 3.3		
	Uehara et al.	2001	Japan	Interoperative (n=100)		50.3 ± 3.6		49.2 ± 2.9		54.1 ± 3.0		
	Uehara et al.	2001	Japan	CT scans (n=100)		48.3 ± 5.4		46.6 ± 3.6		53.8 ± 6.6		
	Yoshioka et al.	1989	Canada	Cadaver study (n=31)		48.0 ± 5.9		45.0 ± 3.9		52.0 ± 5.7		
ML (mm)	This study		France	CT scans (n=100)	TEA	73.7 ± 6.0	(59.7 - 86.4)	68.9 ± 3.5	(59.7 - 76.3)	78.6 ± 3.4	(71.8 - 86.4)	*<0.0001*
					PTM	73.7 ± 5.9	(58.3 - 86.2)	68.9 ± 3.6	(58.3 - 76.8)	78.4 ± 3.4	(71.5 - 86.2)	*<0.0001*
					ATT	71.9 ± 5.2	(58.8 - 85.6)	68.1 ± 3.2	(58.8 - 74.3)	75.7 ± 3.9	(66.1 - 85.6)	*<0.0001*
	Kwak et al.	2007	Korea	CT scans (n=200)		71.9 ± 5.6		67.6 ± 3.1		76.1 ± 4.0		
	Uehara et al.	2001	Japan	Interoperative (n=100)		71.4 ± 5.0		69.5 ± 3.4		77.9 ± 4.1		
	Uehara et al.	2001	Japan	CT scans (n=100)		74.3 ± 6.6		71.7 ± 4.0		83.0 ± 6.2		
	Yoshioka et al.	1989	Canada	Cadaver study (n=31)		76.0 ± 6.2		73.0 ± 4.5		81.0 ± 4.5		
	Mensch & Amstutz	1975	USA	Radiographic study (n=53)		76.2 ± 7.0		69.9 ± 2.7		81.2 ± 4.5		
	Mensch & Amstutz	1975	USA	Cadaver study (n=30)		74.9 ± 6.1		70.1 ± 2.8		80.3 ± 3.7		
ML/AP (ratio)	This study		France	CT scans (n=100)	TEA	1.60 ± 0.11	(1.39 - 2.07)	1.59 ± 0.10	(1.39 - 2.07)	1.61 ± 0.11	(1.42 - 1.93)	*0.6180*
					PTM	1.59 ± 0.10	(1.40 - 1.97)	1.59 ± 0.10	(1.45 - 1.96)	1.60 ± 0.11	(1.40 - 1.97)	*0.5772*
					ATT	1.44 ± 0.18	(1.04 - 1.99)	1.51 ± 0.12	(1.28 - 1.99)	1.36 ± 0.20	(1.04 - 1.74)	*<0.0001*
	Kwak et al.	2007	Korea	CT scans (n=200)		1.57		1.56		1.58		
<PTM (deg)	This study		France	CT scans (n=100)		1.6 ± 5.1	(-12.4 - 14.5)	1.1 ± 5.5	(-12.4 - 14.5)	2.1 ± 4.7	(-9.0 - 10.8)	*0.3289*
<ATT (deg)	This study		France	CT scans (n=100)		-14.8 ± 7.2	(-29.9 - 14.6)	-15.6 ± 6.3	(-28.0 - 1.2)	-13.9 ± 8.1	(-29.9 - 14.6)	*0.2440*

P values less than .05 are significant. <PTM indicates angle in transverse plane between PTM and TEA (positive = internal rotation of PTM). <ATT indicates angle in transverse plane between ATT and perpendicular bisector of the TEA (positive = internal rotation of ATT).

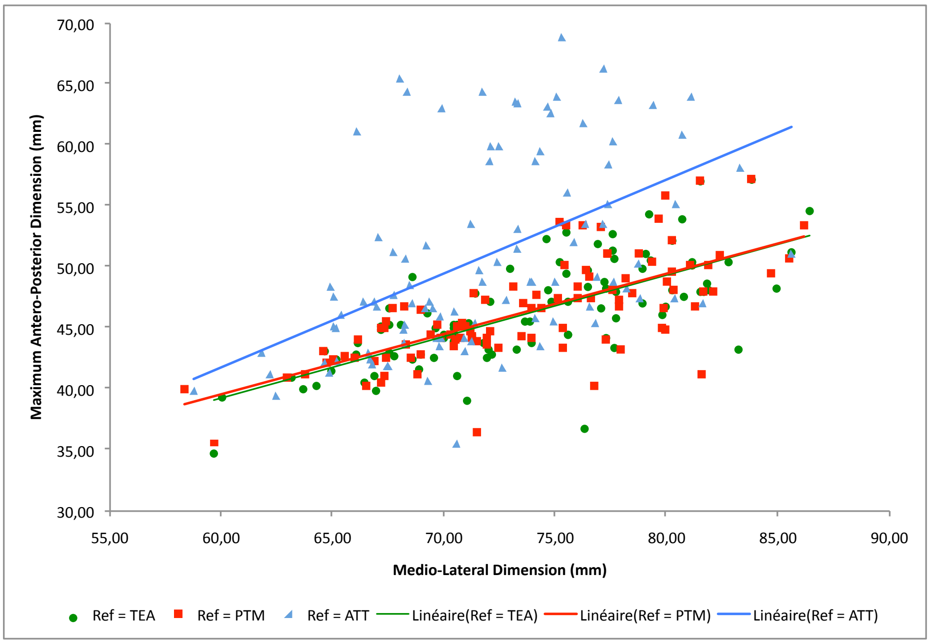

Figure 3: Ratio AP max/ML with the 3 Reference axis (TEA : green circle, PTM : square red, ATT : blue triangle). Note that the regression line with PTM and TEA as reference axis are nearly identical.

A clear asymmetry of tibial plateaus was observed at most levels defined by Westrich and Haas[33]. In most cases, the lateral AP dimensions were smaller than medial AP dimensions, which refer to as "typical asymmetry", The asymmetry was always more pronounced when measurements were aligned to the ATT axis. In a number of cases, the plateau dimensions were almost symmetrical ($0.95 \leq AP_L/AP_M < 1.05$) and in some cases we observed a reversed asymmetry ($AP_L / AP_M \geq 1.05$). The difference in plateau asymmetry using ATT axis versus PTM or TEA is statistically significant at all levels ($p<0.0001$) (Table 2 and Figure 4).

Table 2: Dimensions of medial and lateral tibial plateaus

Parameter	Author	Year	Source	Reference Axis	30% ML Mean ± SD	30% ML (min - max)	20% ML Mean ± SD	20% ML (min - max)	10% ML Mean ± SD	10% ML (min - max)
AP medial (mm)	This study		France	TEA	50.4 ± 4.5	(41.9 - 59.6)	45.4 ± 4.3	(37.6 - 58.7)	34.9 ± 3.7	(25.2 - 44.6)
				PTM	50.4 ± 4.4	(42.5 - 60.1)	45.2 ± 4.2	(37.1 - 58.5)	34.8 ± 3.6	(27.2 - 44.5)
				ATT	53.3 ± 5.5	(42.2 - 64.5)	48.5 ± 5.1	(37.3 - 59.3)	37.2 ± 5.1	(24.3 - 47.7)
	Westrich et al.	1995	USA	?	50.6 ± 5.8	(38.0 - 65.0)	47.4 ± 4.8	(55.0 - 62.0)	37.9 ± 4.2	(28.0 - 45.0)
AP lateral (mm)	This study		France	TEA	45.3 ± 4.6	(33.8 - 57.9)	42.0 ± 3.9	(33.6 - 54.7)	35.3 ± 3.6	(26.8 - 45.2)
				PTM	45.6 ± 4.5	(33.7 - 57.0)	42.3 ± 4.0	(33.3 - 55.0)	35.5 ± 3.6	(28.0 - 45.2)
				ATT	44.2 ± 4.7	(33.8 - 58.1)	40.3 ± 3.6	(32.4 - 50.9)	30.8 ± 4.0	(21.5 - 40.6)
	Westrich et al.	1995	USA	?	41.6 ± 5.4	(27.0 - 54.0)	41.0 ± 4.9	(32.0 - 55.0)	34.8 ± 4.5	(27.0 - 45.0)
AP lateral / AP medial (ratio)	This study		France	TEA	0.90 ± 0.06	(0.77 - 1.08)	0.93 ± 0.07	(0.76 - 1.12)	1.02 ± 0.12	(0.70 - 1.42)
				PTM	0.91 ± 0.05	(0.79 - 1.11)	0.94 ± 0.06	(0.78 - 1.09)	1.03 ± 0.11	(0.80 - 1.28)
				ATT	0.83 ± 0.08	(0.72 - 1.31)	0.84 ± 0.09	(0.64 - 1.22)	0.84 ± 0.15	(0.48 - 1.26)
	Westrich et al.	1995	USA	?	0.82 ± 0.09	(0.60 - 1.16)	0.87 ± 0.08	(0.74 - 1.16)	0.92 ± 0.09	(0.70 - 1.14)
AP lateral minus AP medial (mm)	This study		France	TEA	5.08 ± 3.22	(-3.75 - 11.88)	3.35 ± 3.26	(-5.17 - 13.39)	-0.42 ± 4.09	(-11.06 - 13.51)
				PTM	4.78 ± 2.72	(-5.34 - 11.24)	2.86 ± 2.85	(-3.79 - 11.23)	-0.71 ± 3.78	(-8.14 - 8.37)
				ATT	9.05 ± 4.74	(-13.69 - 17.77)	8.19 ± 4.70	(-9.24 - 20.99)	6.41 ± 6.49	(-8.11 - 23.46)

Parameter	Author	Year	Source	Reference Axis	30% ML $AP_M>AP_L$	30% ML $AP_M=AP_L$	30% ML $AP_M<AP_L$	20% ML $AP_M>AP_L$	20% ML $AP_M=AP_L$	20% ML $AP_M<AP_L$	10% ML $AP_M>AP_L$	10% ML $AP_M=AP_L$	10% ML $AP_M<AP_L$
Tibial asymmetry (%)	This study		France	TEA	87%	11%	2%	67%	28%	5%	22%	40%	38%
				PTM	85%	14%	1%	62%	34%	4%	21%	39%	40%
				ATT	96%	1%	3%	95%	3%	2%	76%	16%	8%

P values less than .05 are significant. <PTM indicates angle in transverse plane between PTM and TEA (positive = internal rotation of PTM). <ATT indicates angle in transverse plane between ATT and perpendicular bisector of the TEA (positive = internal rotation of ATT).

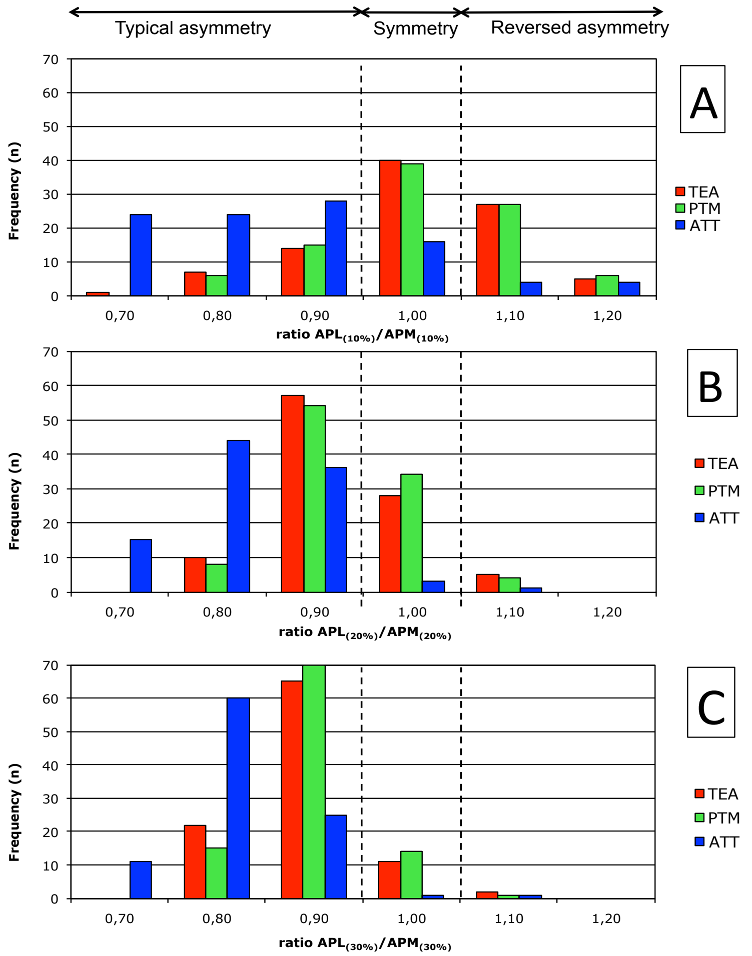

Figure 4: Histograms representing frequency of tibial AP Lateral/AP Medial ratios : (A) at 10%; (B) at 20%; and (C) at 30% of the mediolateral width as defined by Westrich.(33) We considered that when the AP_L/AP_M ratio was between 0.95 and 1.05 the asymmetry was negligible.

Discussion

There is little or no consensus in the literature over the ideal rotational alignment of the tibial component in TKA. Significant variations in the final rotation can be observed depending on the techniques and landmarks. Eckhoff and Johnston[34] evaluated four techniques and observed a variation of 21°. Our hypothesis was that the design and aspect ratio of the tibial component influence the intra-operative choice of rotational reference axis.

In this study we analyzed the morphology of the proximal tibia using CT and we repeated all measurements in alignment with the three common reference axes (TEA, PTM, and ATT). We used the technique of projection of TEA on tibia described by Akagi and Oh[21], and Matsui and Kadoya[35].

The use of 3-D reconstructions of medical images for descriptive anatomic studies or for examination of pathologic lesions is well documented in the literature[21, 35-38]. The use of CT has numerous advantages over cadaver studies. The number of subjects available is greater and their demographic data are accessible. The digitization of relevant points using a computer screen renders the process more accurate because the reconstructed knee is viewed with the ideal magnification and spatial orientation. Once digitized, points remain clearly marked and their placement may be corrected a posteriori if need be. The strengths of this study therefore can be summarized as precision of measurements and selection of suitable subjects. The weaknesses of the study include uncertainty about the exact accuracy of 3-D bone reconstructions of DICOM images. It is also important to note that the reliability of preoperative CT projections of the TEA onto the tibial plateau is uncertain because: (i) external rotation of the tibia relative to the femur is increased in athritic knees,[34, 35] which could explain the small angles observed between PTM and TEA in this study and (ii) CT scans are taken on non-weight bearing knees[9].

Some studies suggest that aligning the tibial component with the center of ATT could be beneficial for patello-femoral tracking and anterior knee pain. Barrack and Schrader[2] compared two groups of TKA patients and observed that in the pain-free group the tibial component was aligned with the center of ATT, (with variations from 8° internal to 12° external rotation), whereas in the group suffering from anterior pain the tibial component was rotated internally by 6.2° relative to the ATT. Huddlestone and Scott[19] reported that using the self-adjusting technique to align the tibial plate with the femoral component, the tibial plate aligns itself approximately 5.2°±5.0° externally relative to the medial margin of the ATT. This corresponds to the junction of the medial and middle third of the tibial tubercule. However, a wide range of values was observed from 10° internal rotation to 15° external rotation and the authors emphasize that, in cases of systematic alignment to the tibial tubercule, 5% of the patients may have a severe malrotation. Ikeuchi and Yamanaka[39] also observed wide variations in rotational alignment while using the self-adjusting technique, with a range from 10mm medial to 9 mm lateral with respect to the medial margin of the ATT and recommend using fixed landmarks rather than the self-adjusting technique.

Alignment of the tibial component to the ATT could induce errors, particularly in cases of patellofemoral dysplasia, where the ATT is often too lateral[40-43]. Such alignment in case of patellofemoral dysplasia allows patellar realignment but can induce a mismatch relative to the femoral component. This can explain why we observed patients with major external rotation of the ATT axis and why Barrack and Schrader[2] and Huddleston and Scott[19] observed such great variations between optimal rotation and tibial tubercule.

Satisfying simultaneously alignment with the ATT and optimal bone coverage can be difficult. In a study of 20 cadaver knees, Lemaire and Pioletti[22] reported a mean differential angle of 9.8° for the Insall-Burnstein II prosthesis, between position for optimum bone coverage and alignment with the ATT.

Numerous studies reported tibial morphometric dimensions from cadaver specimens[18, 44], interoperative measurements[45, 46], or CT data[45], but rotational reference axis in these studies were not always clearly defined, whence the inconsistent results. Yoshioka and Siu[18] measured the tibial plateau parallel to its anterior margin, whereas Uehera and Kadoya[46] and Kwak and Surendran[44] were aligned to the TEA and neither Cheng and Lung[45] nor Westrich and Haas[33] specified their reference axes.

Our data reveal that alignment of the tibial component with the ATT requires external rotation up to 30° relative to the PTM. The AP and ML dimensions and their aspect ratios measured in this study are similar to those reported in the literature (Table 1). We found that the ML/AP aspect ratio varies with gender, as reported by Kwak and Surendran[44] Interestingly, we observed that aspect ratios were significantly different when measurements were aligned with ATT axis in comparison with PTM and TEA. We also observed a greater dispersion of aspect ratios while using ATT as the rotational reference, which can lead to greater difficulty in covering the resected surface with a single design. Comparing our data with the dimensions of tibial components available on the market, it is clear that adaptation is easier to obtain if the tibial plate is aligned to the PTM or TEA rather than the ATT (Figure 5).

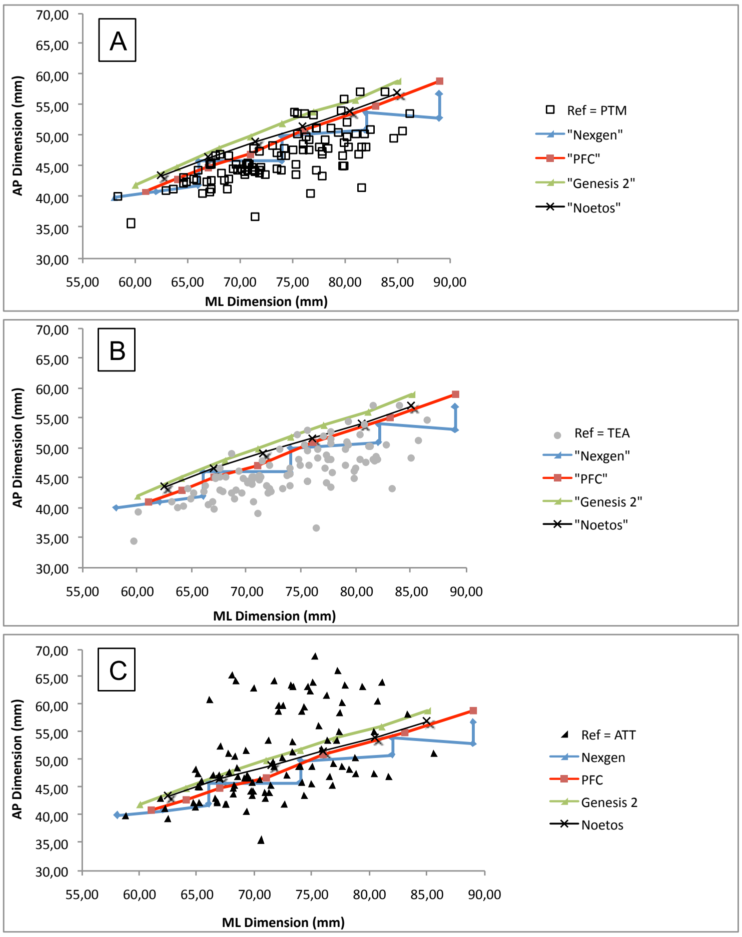

Figure 5: Comparison of Ratio AP/ML as measured according the 3 reference rotational axis in our study (A: PTM, B: TEA and C: ATT) with ratios in 4 different TKA available on the market: NexGen, (Zimmer Warsaw IN, USA), PFC (DePuy, Warsaw IN, USA), Genesis II (Smith&Nephew, Memphis, TN, USA), Noetos (Tornier, Montbonnot, France).

In our series, the AP dimension is greater on the medial plateau in most knees, and the ideal prosthetic tibial plate should theoretically replicate this asymmetry[10, 11, 13, 33, 38, 47], but asymetric components present difficulties in intraoperative adjustments[10, 22, 44]. As in the study of Westrich and Hass[33] we found a few symmetric plateaus and even inversely asymmetric plateaus with AP dimension greater on the lateral plateau when measurements were aligned with TEA (15% of the knees) or PTM (17% of knees). In these patients the use of asymmetric components, with smaller lateral plateau would reduce bone coverage considerably. In case of alignment of the tibial component with the ATT axis, the asymmetry between medial land lateral plateaus is exacerbated, with differences between AP_M and AP_L reaching 21mm. It therefore seems particularly difficult to obtain both complete bone coverage and alignment with ATT while using a symmetric tibial component. When implanting a symmetric tibial component in alignment with ATT, the surgeon is left with two options: If the medial side is referred to for sizing then the tibial base plate will overhang laterally. If the lateral side is chosen as reference, it is necessary to decrease tibial component size with two consequences: (i) medial bone coverage can be inadequate and (ii) femoral component size must eventually be modified. If the surgeon aligns the tibial base plate to the ATT, the use of asymmetric implant could be beneficial, but their use is not simple because of extent of variation in aspect ratio.

The use of mobile bearing tibial plates theoretically allows decoupling of bone coverage and rotational alignment. Therefore, if the metallic base plate is aligned to the PTM to obtain optimum coverage, the polyethylene liner can align automatically to the position of the femoral component. This ability of mobile bearing TKA to compensate for tibial malrotation is shown to reduce femoral stresses[48], but is not proven for prevention of patellar tilt or subluxation[49, 50].

Conclusion

This study confirms that definitions of tibial morphology can vary considerably depending on the reference axis used. The choice of alignment with TEA, PTM or ATT axis restricts component design and allows little variation if we wish to optimize simultaneously prosthetic coverage and alignment with the extensor mechanism.

From this study, the use of the anterior tibial tubercule as a rotational landmark for the tibial component raises several critics. First, orientation of the ATT axis proved to vary considerably, from 14° internal to 29° external rotation with respect to the TEA, which can induce excessive external rotation. Second, asymmetry between medial and lateral tibial plateaus is more pronounced is case of alignment with the ATT, which can compromise bone coverage of tibial plateaus. Finally, variations in tibial plateau morphology were greater while using ATT as the reference, which can lead to greater difficulty in covering the resected surface with a single design.

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7. Morphometric analysis of the distal femur: TKA femoral components should be more trapezoidal

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Abstract

The morphology of the distal femur and of TKA femoral components has been largely analysed through the ‘aspect’ ratio (wide/narrow), but little is known about the ‘trapezoidicity’ (rectangular/trapezoidal) variations. This study aimed to quantify additional morphologic characteristics of the distal femur and identify anatomic features associated with higher risks of prosthetic oversizing or overhang.

We analyzed the shape of 114 arthritic knees that underwent primary TKA using their pre-operative CT scans. The ‘aspect ratio’ and ‘trapezoidicity ratio’ were quantified and the postoperative prosthetic overhang was calculated. We compared the analysed morphologic characteristics to those of five TKA models.

Both ‘aspect ratio’ and ‘trapezoidicity ratio’ of femurs had considerable variations. Femoral ‘trapezoidicity’ was mostly due to inward curve of the medial cortex. Overhang was correlated to the ‘aspect ratio’ (more in narrow femurs), ‘trapezoidicity ratio’ (more in trapezoidal femurs), and tibio-femoral angle (more in valgus knees).

This study shows that ‘rectangular-trapezoidal’ variability of the distal femur cannot be ignored. Most of the tested femoral implants appeared to be excessively rectangular when compared with the bony contours of the distal femur. We hypothesized from this study that design of TKAs should be more focused on the trapezoidal/rectangular analysis.

Introduction

When implanting a Total Knee Arthroplasty (TKA), a prime surgical goal is to optimize bone coverage, while avoiding prosthetic overhang, which is proven to compromise clinical outcomes[1-3]. However, prosthetic over-sizing after TKA is reported at a frequency up to 66%[1] and 76%[3]. The reasons for such high incidence of prosthetic over-sizing are multiple and non-exclusive: (i) morphology of the distal femur and proximal tibia is highly variable in the human population; (ii) implants are available in a limited range of sizes and morphologies for economic reasons and (iii) surgeons are often obliged to compromise when selecting femoral sizing, tibial sizing, ligament balancing and components rotation, all of which are inter-related.

Over the past decade, special attention was paid to the 'aspect ratio' of the distal femur[2, 4-6], and consequently several manufacturers included narrower versions – also termed "gender specific" – of their femoral components, in order to improve bone-implant fit[6-10]. Recently, Mahfouz et al.[11] described the complex variations in femoral morphology and suggested that they cannot be described solely and simply as 'wide' or 'narrow'. The authors showed that the distal femur morphology in the transverse plan could also be described as 'rectangular' versus 'triangular', and 'symmetric' versus 'asymmetric'. The authors quantified these variations with three normalized ratios, from which they distinguished six morphotypes of the distal femur, which may be related to gender and ethnicity. Therefore, a question emerges: do we need specific implant design to fit with all these anatomic variations? No studies established whether prosthetic overhang is associated with specific morphotypes such as narrow or asymmetric femurs. It is also still controversial whether the introduction of narrower implants improved the clinical outcomes after TKA[9, 10].

The wide/narrow shape of femoral components in different TKA designs has been largely analyzed and quantified through the 'aspect' ratio. However, little is known about the trapezoidal/rectangular and symmetric/asymmetric shape of implants available on the market. The goals of the present study were to (i) analyze the morphologic characteristics of arthritic femurs through these new ratios (ii) identify the anatomic features associated with a higher risk of oversizing and (iii) analyze the shape of various TKA designs in relation to these ratios. Our hypothesis were that both narrow and trapezoidal femurs have a higher risk of femoral component overhang after TKA and that 'trapezoidicity' ratio of prosthetic femoral components varies from one design to another.

Material and Methods

Patient demographics

A consecutive series of 114 knees (63 females and 51 males) in 112 patients that underwent primary TKA between January 2008 and June 2009 by the senior surgeon (MB) was retrospectively analyzed. A computed tomography (CT) scan is performed as part of a routine preoperative planning for TKA at our institution[1, 5]. The series excludes patients with previous surgery or trauma or with an unclear CT scan due to artifacts from surrounding metal or contrast agent. The mean age of the patients was 72 years (range; 56 to 88), mean weight was 81 kg (range; 45 to 125) and mean height was 168 cm (range 144 to 194). The indication for TKA was medial compartment osteoarthritis in 81 knees, lateral compartment osteoarthritis in 15 knees, bi-compatimental osteoarthritis in 8 knees, patellofemoral osteoarthritis in 6 knees, and spontaneous necrosis of the medial condyle in 4 knees. On the preoperative long leg radiographs the mean tibiofemoral angle (TFA) - available for 107 knees - was 176° (range 160° to 194°): 80 knees had a varus alignment with a TFA angle less than 180° and 27 knees had a valgus alignment with a TFA angle greater than 180°. All patients received HLS Noetos

(Tornier SA, Montbonnot, France) implants. All patients signed a written informed consent form and the institution ethics committee approved the study.

Surgical Technique

The tibia was cut first, followed by the femur with a posterior reference technique. The tibial and femoral cuts were orthogonal to the mechanical axis so as to obtain a 180° axis. Rotation of the femoral component was aligned along the surgical transepicondylar axis, localized on the preoperative CT scan for each patient. In valgus knees, rotation of the femoral component was adjusted to reduce resection of the posterolateral condyle, in order to compensate for lateral hypoplasia[12]. The mediolateral alignment of the femoral component was always centred over the distal resection. Rotation of the tibial component was aligned with respect to the centre of the anterior tibial tuberosity (ATT). The size of the femoral component was determined based on the instrumentation so as to prevent any notch from being created along the anterior femoral cortex. The size of the tibial component was adapted to the size of the femoral component and adjusted to match the cortical contours of the tibial cut.

Measurement protocol

The patients had been scanned following an identical protocol using a 64-slice multidetector scanner (Siemens® Sensation, Munich, Germany) in the supine position with the knees fully extended and the legs fixed in neutral rotation. The hip was scanned from the anterior inferior iliac spine to the lesser trochanter and the knee from 50 mm above the superior patellar margin to the bottom of the anterior tibial tuberosity. We used the image-processing software OsiriX (Pixmeo SARL, Bernex, Switzerland) dedicated to DICOM images[13, 14], and a 24-inch external monitor for optimal image magnification. The imaging software enabled simultaneous visualization of CT cross-sections in three planes (frontal, sagittal and transverse), which helped accurately identify two reference transverse sections: First, the slice showing the most proximal attachment of the posterior cruciate ligament[15], from which the maximal anteroposterior size was measured (perpendicular to the posterior condylar margin) on the medial (AP_M) and lateral (AP_L) sides; Second, the theoretical distal resection level (10 mm proximal to the most distal condyle) at which the medial and lateral cortical contours were digitized using the 'open polygon' function, recording point coordinates at intervals of 1–2 mm, from the most anterior tips of the trochlea to the most posterior points of the condyles (Figure 1). Finally, the coordinates of digitized contours were exported using OsiriX, to a comma-separated variables file, which could be manipulated in spreadsheets using Microsoft Excel (Microsoft Corp, Redmond, WA). It is worth noting that all points were digitized on the same native CT slice, which was assumed to be orthogonal to the femoral mechanical axis, within ±10º of error, hence negligible errors due to misalignment of the femur within the scanner (maximum error = $1 - \cos 10^\circ = 1.5\%$).

Morphologic characteristics

The principal dimensions were calculated as described previously[1] from the 3D coordinates in the spreadsheets using mathematical functions (Figure 1). The maximum anteroposterior dimension at the medial (AP_M) and the lateral (AP_L) condyles was used to calculate an 'average AP' dimension. The mediolateral (ML) dimension was measured on the theoretical distal resection slice at three levels: the posterior region (ML_P), 10mm anterior to the posterior condylar margin, the central region (ML_C) at 50% of the 'average AP' dimension, and the anterior region (ML_A), at 75% of the 'average AP' dimension.

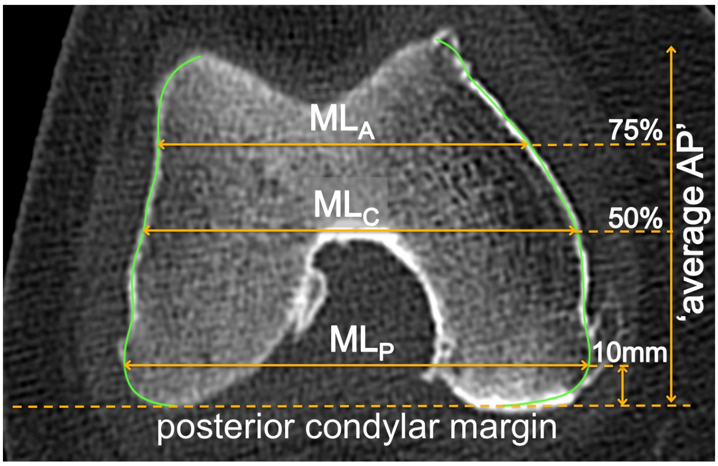

Figure 1: Transverse CT slice at the distal resection level of the femur (10mm above the most distal point on the medial condyle), indicating the digitized femoral cortical contours (green), and illustrating the main measured dimensions (yellow). The mediolateral (ML) dimensions were measured at 3 levels: the posterior region (ML_P), 10mm from the posterior condylar margin, the central region (ML_C) at 50% of the 'average AP' dimension, and the anterior region (ML_A), at 75% of the 'average AP' dimension.

The three femoral ratios defined by Mahfouz et al.[11] were deduced (Figure 2). The 'aspect' ratio (ML/AP) ratio quantified how wide or narrow the shape is. The 'trapezoidicity' ratio (ML_P/ML_A) ratio quantified how rectangular or trapezoidal the shape is. The 'asymmetry' ratio (AP_L/AP_M) quantified how symmetric or asymmetric the condyles are. For each ratio, we defined the shape relative to the median value, e.g. femurs with aspect ratio below the median were considered "narrow" and femurs with trapezoidicity ratio above the median were considered "trapezoidal". We also quantified the medial and lateral 'narrowing angles' in the anterior and central zones (α and β) (Figure 3).

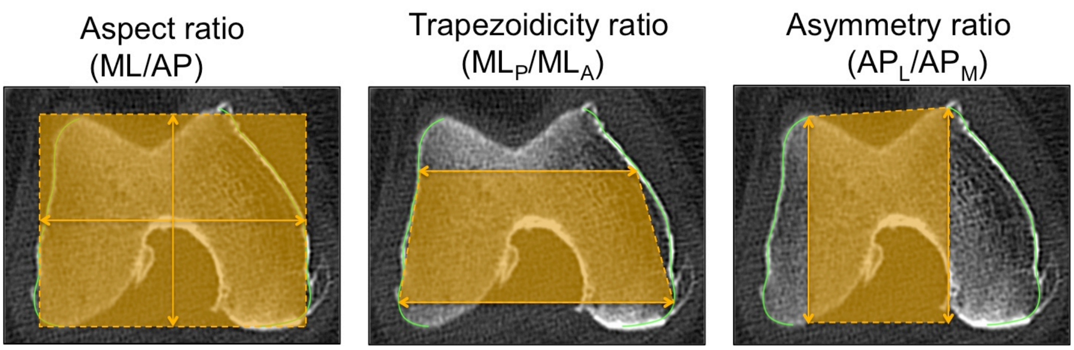

Figure 2: Illustration of the three geometric ratios calculated to characterize the morphology of the distal femur: the 'aspect' ratio (ML/AP) ratio quantifies how wide or narrow; the 'trapezoidicity' ratio (ML_P/ML_A) ratio quantifies how rectangular or trapezoidal; the 'asymmetry' ratio (AP_L/AP_M) quantifies how symmetric or asymmetric the condyles are.

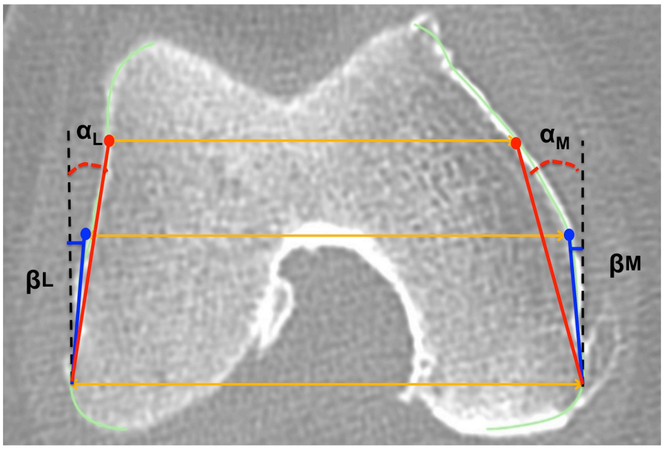

Figure 3: Narrowing angles were measured between the line perpendicular to the posterior Condylar Margin and the cortex at 50% (angle ß or 'central narrowing angle') and at 75% (angle α or 'anterior narrowing angle') of the anteroposterior dimension (AP average). Angles were measured both on the medial (α_M and $ß_M$) and on the lateral side (α_L and $ß_L$).

Prosthetic overhang

We compared the dimensions (ML_A and ML_C) measured on the preoperative CT scan to the corresponding dimensions of the implanted component, provided by the manufacturer, using previously published method[1]. The 'size discrepancy' was calculated in millimetres (positive when the implanted component was wider than the resected bone, and negative when it was narrower).

Specimen implants

The authors formed a sample of 12 TKA femoral components (explants) and identified each specimen by its laser marking to determine its manufacturer, model, serial number, size and side. The specimens were each scanned using a three-dimensional (3D) optical scanning machine (ATOS II, GOM mbH, Braunschweig, Germany) and its photogrammetric analysis software (TRITOP, GOM mbH, Braunschweig, Germany). The system has measurement resolution of 0.05 mm and overall accuracy of ±0.01 mm. The 3D reconstructions of the specimens were manipulated using the software ProEngineer (Needham, MA, USA) to calculate the equivalent AP and ML dimensions as those recorded from the patient CT scans.

Statistical analysis

The Mann-Whitney test was used to verify significance in differences (dimensions, ratios and angles) between males/females and between knees with/without prosthetic overhang. The ascendant linear regression was used to evaluate the impact of some factors on oversizing. The studied factors (explanatory variables) were the three ratios (aspect ratio, trapezoidicity ratio, asymmetry ratio), knee alignment (varus or valgus) or gender (male or female). Since some explanatory variables were correlated, the variance inflation factor (VIF) was calculated for each of the variables in order to evaluate the impact of the multicollinearity on the variance of the corresponding estimated coefficient. It was always inferior to 5 meaning that the effect of multicollinearity on the estimations could be considered as negligible. No control for multiple testing was applied. The above analysis were performed using R software. The level of statistical significance was set at 0.05.

Results

Morphometric analysis

The AP and ML dimensions were all significantly greater in males than in females ($p<0.001$) (Table 1). The 'aspect ratio' was significantly greater in males (1.19±0.08; range 0.98 to 1.31) than in females (1.14±0.06; range 1.02 to 1.28) ($p<0.001$), indicating that females had narrower femurs. The 'trapezoidicity ratio' and 'asymmetry ratio' were nearly identical for both genders (Table 2). Linear regression revealed no correlation between geometric ratios and age, BMI or TFA. The 'aspect ratio' and 'trapezoidicity ratio' had considerable inter-individual variations. Taking median values as limits to characterize knees as wide/narrow or rectangular/trapezoidal: 37 knees (32.5%) were narrow-trapezoidal, 20 knees (17.5%) were narrow-rectangular, 20 knees (17.5%) were wide-trapezoidal, and 37 knees (32.5%) were wide-rectangular (Figure 4. In essence, narrow femurs were more frequently trapezoidal, whereas wide femurs were more frequently rectangular (Spearman coefficient correlation between 'aspect ratio' and 'trapezoidicity ratio' = -0.39, $p<0.001$).

Table 1: Distal femoral dimensions

	Series		Men		Women		
	Mean ± SD	(min - max)	Mean ± SD	(min - max)	Mean ± SD	(min - max)	***p values*** [1]
Antero-posterior							
AP_M (mm)	59.1 ± 4.3	(50.6 - 71.1)	62.3 ± 3.5	(53.9 - 71.1)	56.5 ± 2.8	(50.6 - 62.9)	*<0.001*
AP_L (mm)	62.8 ± 5.1	(52.5 - 73.4)	66.6 ± 3.8	(58.9 - 73.4)	59.7 ± 3.6	(52.5 - 67.9)	*<0.001*
Medio-lateral							
ML_M (mm)	59.5 ± 6.8	(44.5 - 75.4)	64.6 ± 5.5	(49.7 - 75.4)	55.3 ± 4.5	(44.5 - 65.3)	*<0.001*
ML_C (mm)	70.9 ± 7.2	(57.5 - 89.2)	76.8 ± 5.7	(60.3 - 89.2)	66.2 ± 4.1	(57.5 - 75.0)	*<0.001*
ML_P (mm)	71.9 ± 7.2	(58.5 - 87.6)	78.0 ± 5.1	(64.0 - 87.6)	67.0 ± 4.3	(58.5 - 78.0)	*<0.001*

[1] Between women and men (Mann-Whitney Test)

Table 2: Distal femoral ratio and angles

		Series		Men		Women		
		Mean ± SD	(min - max)	Mean ± SD	(min - max)	Mean ± SD	(min - max)	*p values* [1]
Antero-posterior								
Aspect ratio	ML/AP	1.16 ± 0.07	(0.98 - 1.31)	1.19 ± 0.08	(0.98 - 1.31)	1.14 ± 0.06	(1.02 - 1.28)	*<0.001*
Trapeziodicity ratio	ML_P/ML_A	1.21 ± 0.08	(1.06 - 1.46)	1.21 ± 0.08	(1.06 - 1.45)	1.22 ± 0.09	(1.06 - 1.46)	*0.667*
Asymmetry ratio	AP_L/AP_M	1.06 ± 0.05	(0.91 - 1.17)	1.07 ± 0.05	(0.96 - 1.17)	1.06 ± 0.05	(0.91 - 1.17)	*0.171*
Anlges [2]								
Lateral narrowing	α_L	9.6 ± 4.8	(-6.4 - 22.0)	12.4 ± 3.7	(5.6 - 22.0)	7.5 ± 4.4	(-6.4 - 15.4)	*<0.001*
	β_L	5.6 ± 7.0	(-15.2 - 22.6)	9.8 ± 5.0	(-2.2 - 22.6)	2.5 ± 6.7	(-15.2 - 16.1)	*<0.001*
Medial narrowing	α_M	17.4 ± 2.9	(10.3 - 24.0)	17.3 ± 2.9	(11.2 - 24.0)	17.4 ± 2.8	(10.3 - 22.8)	*0.773*
	β_M	9.8 ± 5.1	(-0.2 - 24.4)	9.7 ± 5.1	(-0.2 - 23.9)	9.9 ± 5.2	(0.9 - 24.4)	*0.893*

[1] Between women and men (Mann-Whitney Test)

[2] Data for angles was missing for 5 men and for 1 woman

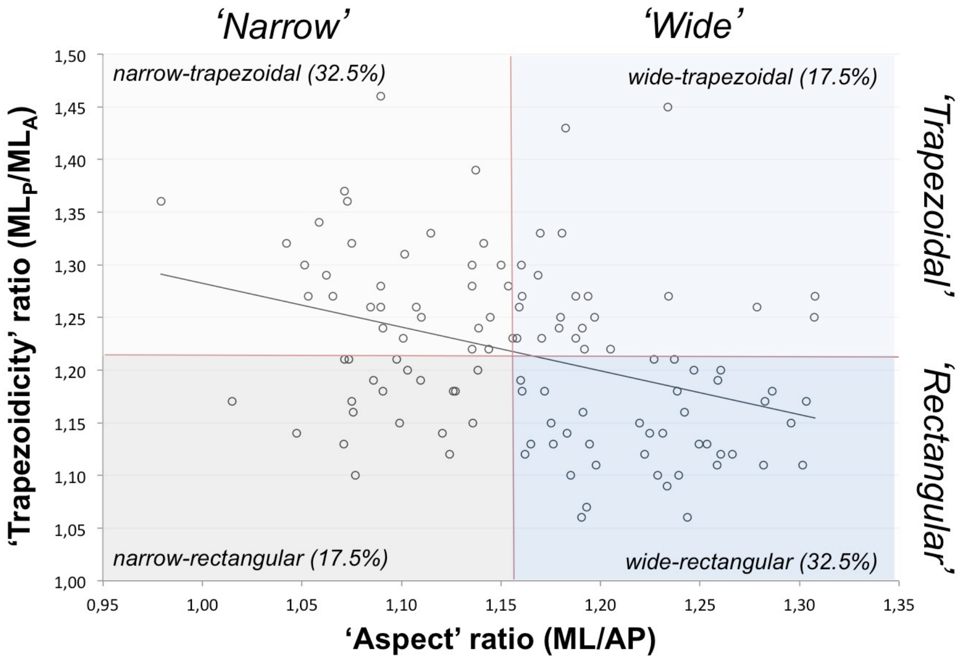

Figure 4: Correlation of 'aspect' ratio (AP/ML) and 'trapezoidicity' ratio (ML_P/ML_A): femurs with aspect ratio below the median value were considered "narrow"; femurs with trapezoidicity ratio above the median value were considered "trapezoidal". Narrow femurs were more frequently trapezoidal than wide femurs (p<0.001).

The scatter plots of digitized cortical contours (Figure 5) illustrate the trapezoidicity and how the cortex narrows anteriorly, by curving inwards on the medial side, and by linear inclination on the lateral side. The *medial* narrowing angles (α_M, 17.4º ±2.9 and β_M, 9.8º±5.1) were almost double the *lateral* narrowing angles (α_L, 9.6º±4.8 and β_L, 5.6º±7.0). The *lateral* narrowing angles were also significantly greater for males (α_L, 12.4º ±3.7 and β_L, 9.8º±5.0) than for females (α_L, 7.5º±4.4 and β_L, 2.5º±6.7) ($p<0.001$), whereas the *medial* narrowing angles were nearly identical for both genders. The narrowing angles and trapezoidicity ratios were smaller for patients with patellofemoral osteoarthritis than for other indications, but this difference was not statistically significant (Figure 6).

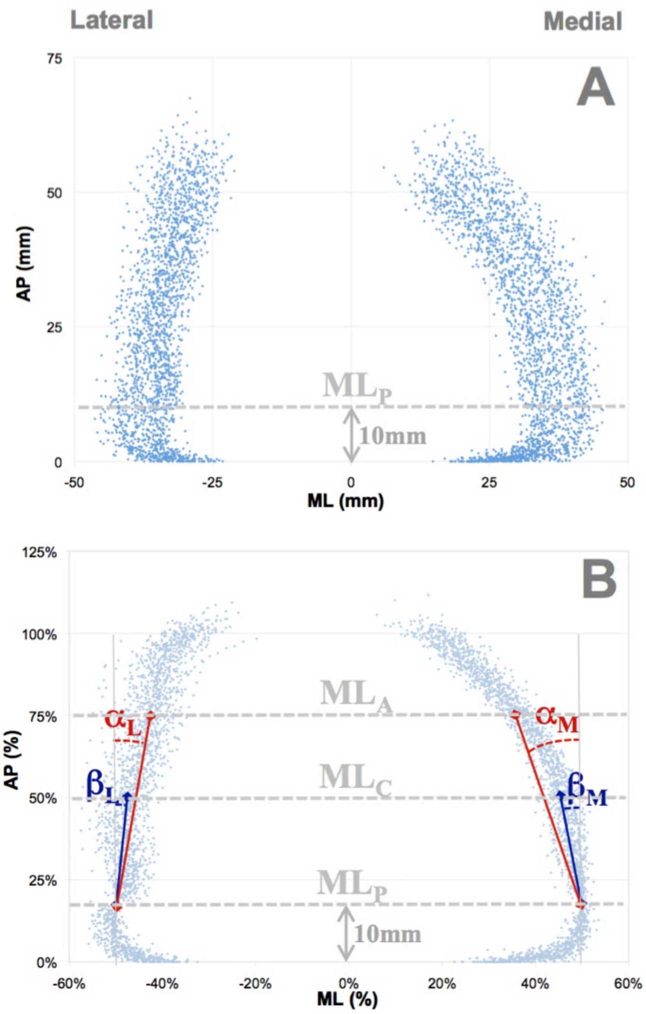

Figure 5: Scatter plots of digitized cortical contours: (A) in absolute dimensions (mm) showing size variations; (B) in relative dimensions (% of 'average AP' and ML_P) showing morphologic variations (NB: convergence of points around the ML_P line used to define relative ML coordinates). The anterior and central 'narrowing angles' on the medial (α_M and β_M) and lateral (α_L and β_L) sides were calculated individually for each knee to better describe 'trapezoidicity'.

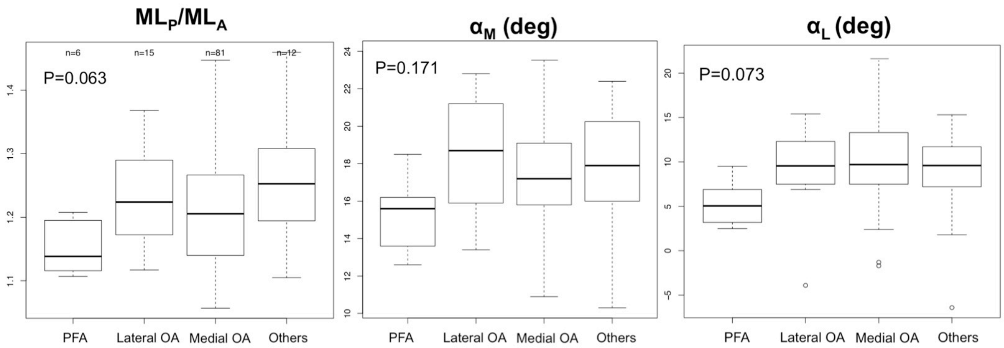

Figure 6: Boxplots showing the trapezoidicity ratios and anterior narrowing angles for patients with different indications: patellofemoral osteoarthritis (PFA, n=6), lateral compartment osteoarthritis (lateral OA, n= 15), medial compartment osteoarthritis (medial OA, n =81) and others (n=12). The p-values were calculated using the Kruskal Wallis test.

Prosthetic overhang

Anterior overhang was observed in 76 patients (67%), where the mean difference in width (ML_A) between bone and implant was 2.2 ± 4.7mm (range; -10 to 13mm). Central overhang was observed in 34 patients (30%), where the mean difference in width (ML_C) between bone and implant was -2.2 ± 4.8mm (range; -15 to 7.7mm). Patients with prosthetic overhang in the anterior area had a narrower and a more trapezoidal femur (respectively p-values =0.006 and 0.014) (Table 3).

Table 3: Prosthetic overhang and undercoverage

		prostethic overhang		**no prosthetic overhang**		
		Mean ± SD	(min - max)	Mean ± SD	(min - max)	***p values*** [1]
Aspect ratio	ML/AP	1.15 ± 0.07	(0.98 - 1.31)	1.19 ± 0.07	(1.04 - 1.31)	*0.006*
Trapeziodicity ratio	ML_P/ML_A	1.23 ± 0.08	(1.10 - 1.46)	1.19 ± 0.09	(1.06 - 1.44)	*0.014*
Asymmetry ratio	AP_L/AP_M	1.06 ± 0.05	(0.91 - 1.17)	1.07 ± 0.05	(0.93 - 1.17)	*0.267*

[1] Between knees with prosthetic overhang and knees without prosthetic overhang (Mann-Whitney Test)

The multivariate analysis indicated that anterior overhang was correlated to the 'aspect ratio' (more overhang in narrow femurs, p=0.002), the 'trapezoidicity ratio' (more overhang in trapezoidal femurs, p=0.002), and the TFA (more overhang in valgus knees, p=0.035). It is noteworthy that TFA was correlated to overhang (multivariate analysis) but uncorrelated to geometric ratios (linear regression). This is probably due to the tendency to implant larger sized femoral components in valgus knees to compensate for hypoplasia of the lateral condyle. Mean femoral overhang was found greater in females than in males, but after adjustment with other variables, the influence of gender appeared to be non significant (p=0.117) (Table 4).

Table 4: Results of the multivariate linear regression

Effect of each variable on prosthetic overhang			
Variable	**estimate**	**Std. error**	***p values*** [1]
Aspect ratio (ML/AP)	-1.378	0.439	*0.002*
Trapeziodicity ratio (ML_P/ML_A)	1.335	0.415	*0.002*
Varus alignment	-1.905	0.889	*0.035*
Male gender	-1.301	0.823	*0.117*

[1] Student t-Test

Specimen implants

The geometries of the five specimen implants can be compared directly to the morphometric findings of this study (Table 5, Figure 7). All implants exhibited excessively high aspect ratios (too large), and all but one implant had insufficiently low trapezoidicity ratios (too rectangular). All implants had insufficiently small lateral narrowing angles, and all but one implant had insufficiently low medial narrowing angles.

Table 5:Distal femoral ratio and angles: implant specimens compared to anatomy

		This study	**Zimmer**	**Zimmer**	**Zimmer**	**DePuy**	**DePuy**	**DePuy**	**DePuy**	**DePuy**	**Stryker**	**Biomet**	**S&N**	**Tornier**
		114 knees	NexGen	Persona [1] 'standard'	Persona [1] 'narrow'	LCS	PFC [2] 'standard'	PFC [2] 'narrow'	Attune [3] 'standard'	Attune [3] 'narrow'	Scorpio	Vanguard	Journey	Noetos
Ratios														
Aspect ratio	ML/AP	1.16	1.16	1.07	1.07	1.09	1.09	1.01	1.10	1.10	1.07	1.06	1.16	1.10
Trapeziodicity ratio	ML_P/ML_A	1.21	1.24	1.28	1.28	1.05	1.17	1.18	1.20	1.28	1.11	1.18	1.25	1.11
Asymmetry ratio	AP_L/AP_M	1.06	1.02	1.08	1.08	1.00	1.08	1.08	1.00	1.00	1.01	1.00	1.01	1.01
Anlges														
Lateral narrowing	α_L	9.6	9.6	8.2	8.2	1.4	5.5	5.4	6.8	9.2	3.2	7.1	7.1	5.9
	β_L	5.6	8.1	3.5	3.5	0.2	2.1	1.8	3.8	8.1	0.1	3.0	3.0	1.0
Medial narrowing	α_M	17.4	12.4	14.6	14.6	4.1	9.6	9.5	11.1	13.5	7.1	9.1	13.8	9.9
	β_M	9.8	4.2	6.5	6.5	0.1	4.2	3.3	4.2	8.5	0.1	3.3	5.4	0.6

[1] Standard version available for sizes 3 to 12; narrow version available for sizes 1 to 11
[2] Standard version available for sizes 1.5 to 6; narrow version only available for size 4
[3] Standard version available for sizes 1 to 10; narrow version available for sizes 3 to 6

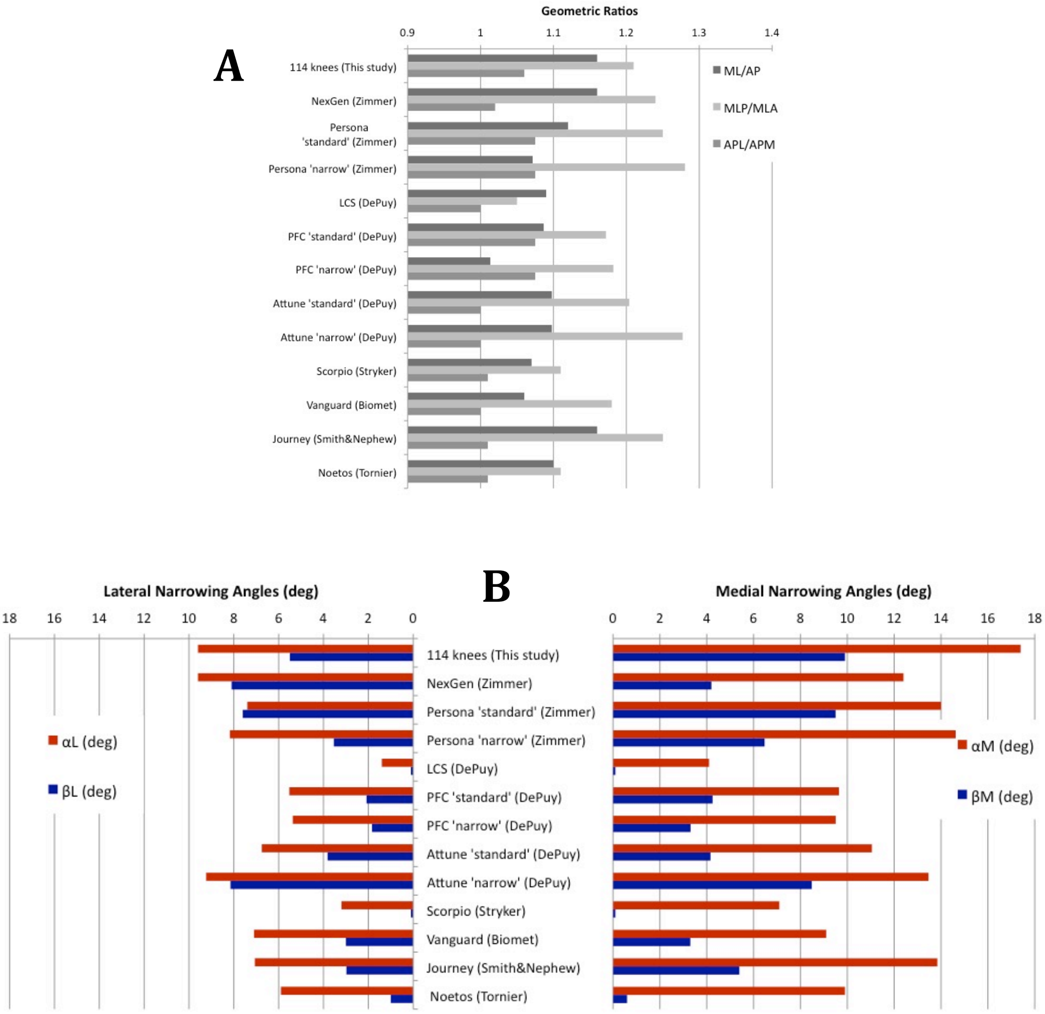

Figure 7: Comparison between measurements from patients with those of 11 different implant models (A) Geometric ratios and (B) Narrowing angles.

Discussion

Two important findings can be emphasized from this study. First, the shape of the distal femur presents more complex variations than previously thought. They cannot be limited to narrow-wide dimension but also to trapezoidal-rectangular, the two ratios characterizing these dimensions having a similar variability. Second, many of the analyzed implants were not trapezoidal enough compared with the native femur, making it challenging to match prosthetic coverage.

Since the beginning of TKA where only one size of femoral component was available, knowledge in knee anatomy and prosthetic design improved significantly[16]. From the early 1970s to the late 1990s, manufacturers increased the range of femoral implant sizes in a proportional way, with the same 'aspect-ratio' (ML/AP) from small to large sizes. In the early 2000s, several anatomic studies under-scored the variability of the 'aspect ratio' of the distal femur[2, 4-6], leading manufacturers to introduce narrower components[6-10]. It is not yet clear whether these implants improve clinical results[9, 10]. It is only recently that more complex shape variability was described on the distal femur and proximal tibia[11]. To our knowledge no investigation focused on the trapezoidal/rectangular shape of the distal femur in TKA design.

This study presents several limitations. First, only one TKA design was implanted in this series and it is unclear whether our conclusions can be extended to other implants. However, it should be noted that the ML/AP aspect ratio of the design used is close to other more widely utilized implants[1]. Second, the patients in this series were all Caucasians and morphologic characteristics cannot be extended to Asian or African populations. Third we analyzed the dimensions in arthritic knees, which differs from a real shape analysis, as conducted by Mahfouz et al.[11] on healthy knees. Finally, we only analysed femoral morphology at the level of the distal cut, and did not investigate geometric variations at the levels of the anterior or posterior cuts, where prosthetic overhang could also cause impingement against soft tissues.

The present work confirms the high variability of the ML/AP 'aspect-ratio' of the distal femur and the higher proportion of narrow femurs in females. It reports also great variations of the ML_P/ML_A 'trapezoidicity ratio', some femurs having a rectangular shape and some having a trapezoidal shape, without gender difference. This confirms the study of Mahfouz et al, who reported ethnic variations but no gender difference for the 'trapezoidicity ratio'[11]. Even if a correlation was observed between these two ratios, with more trapezoidal knees in the narrow group, we found that 17.5% of the knees were wide-trapezoidal and the same proportion were narrow-rectangular.

Overhang of the femoral component in the anterior-distal area was noted in 84% of the females and 54% of the males in our patients[1], which is close to the study of Mahoney et al who reported overhang superior to 3mm in this same area respectively in 57% in women and 32% in men with the Scorpio prosthesis[3]. A higher rate of oversizing was observed in women in these two series but we demonstrate from this study that gender is not an independent risk factor.

Our purpose in this study was to investigate the morphologic and design factors of femoral overhang. We identified with the multivariate analysis three main morphologic risk factors: Patients with preoperative narrow femurs, trapezoidal femurs or valgus alignment had a higher rate of prosthetic overhang. The risk of overhang is also increased when using rectangular implants in trapezoidal femurs as well as when using wide implants in narrow femurs.

Since the work of Hitt et al.[2] a great attention has been paid by manufacturers to adapt TKA design to narrower femurs but our explant analysis shows that rectangular-trapezoidal variations have been underestimated. We observed that implant manufacturers adjusted the trapezoidicity ratios and narrowing angles in more recent TKA designs to better match anatomy (Figure 7). It is interesting to note that the 'trapezoidicity ratio' of the Scorpio prosthesis – which shows a similar rate of anterior overhang - is exactly similar to the Noetos prosthesis implanted in this series[3].

In our series, the comparison of patients and prosthesis 'trapezoidicity ratio' shows that the mediolateral dimensions of the prosthetic component fit both with the posterior and the anterior area only for the more rectangular femurs (Figure 7). For the majority of our patients a normosized component in the posterior area appears to be oversized in the anterior zone. Therefore surgeons often need to compromise and to accept some degree of posterior undercoverage in order to avoid any anterior overhang. This explains why in our series, most of our patients where under-sized at the ML_P and ML_C levels and why better pain score were observed in these patients[1]. To our knowledge, the consequences of posterior and/or distal mediolateral undercoverage is poorly studied and it is unclear whether it may jeopardize the outcomes. Mueller et al.[17] reported increased midflexion instability in case of femoral downsizing and attributed this to decreased posterior offset. Another explanation could be the reduction of mediolateral distance between the tibiofemoral contact points but this was not investigated. Distal femoral undercoverage can also cause insufficient bone-implant contact leading to poor fixation[18] and residual pain due to soft-tissue impingement against sharp edges of resected bone[2].

Even if femoral overhang is largely influenced by patient morphotype and TKA design, we should not underestimate the role of surgical technique. Surgeons may accept mediolateral femoral overhang in some patients to avoid anterior notching in a posterior-referencing technique[19], or to improve flexion stability in an anterior-referencing system[20]. External rotation of the femoral component, when obtained by decreased posterolateral resection, may also require component oversizing[21]. Lastly, the surgeon may be obliged to oversize the femur just to match the tibial size[22].

Conclusion

This study shows that shape variations of the distal femur are not limited to 'wide-narrow' and that 'rectangular-trapezoidal' variability cannot be ignored. Most of the tested femoral implants appeared to be excessively rectangular when compared with the bony contours of the distal femur. We hypothesized from this study that design of TKAs should be more focused on the trapezoidal/rectangular analysis. Frequently femoral oversizing is the consequence of excessively rectangular implants and this should be addressed mostly by designing more trapezoidal implants rather than narrower implants. The data reveals considerable variation of femoral morphotypes, and if the goal of TKA is to optimise bone-implant fit, then the ideal solution would be custom-made implants, unless manufacturers provide additional geometric configurations.

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8. External rotation of the femoral component increases asymmetry of the posterior condyles

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Abstract

Aims: The morphometry of the distal femur was largely studied to improve bone-implant fit in total knee arthroplasty (TKA), but little is known about the asymmetry of the posterior condyles. This study aimed to investigate the dimensions of the posterior condyles and the influence of externally rotating the femoral component on potential prosthetic overhang or under-coverage.

Methods: We analysed the shape of 114 arthritic knees at the time of primary TKA using pre-operative CT scans. The height and width of each condyle were measured at the posterior femoral cut in neutral position, and in 3º and 5º of external rotation, using both central and medial referencing systems. We compared the morphological characteristics with those of 13 TKA models.

Results: In the neutral position, the dimensions of the condyles were nearly equal. External rotation induced asymmetries that were exacerbated using 'medial referencing'. Externally rotating the femoral cut but by 5º with 'central referencing' induced height asymmetry >3 mm in 46%, and width asymmetry >3mm in 32%, while with 'medial referencing' it induced height asymmetry >3 mm in 66%, and width asymmetry >3mm smaller in 69%. The asymmetries induced by rotations were not associated with gender or aetiology.

Discussion: External rotation amplifies the asymmetry between the medial and lateral condyles, and exacerbates prosthetic overhang, particularly in the supero-lateral zone. 'Central referencing' guides result in less potential prosthetic overhang than 'medial referencing' guides.

Take Home Message: Surgeons must be aware of prosthetic overhang that could arise at the posterior condyles, which are hardly visible during surgery, and which could induce impingements with the popliteus tendon or the joint capsule.

Introduction

In total knee arthroplasty (TKA), the prosthetic condyles should ideally fit with the contours of resected bone, without overhang[1, 2] and minimal uncovered areas[3]. A high incidence of bone-implant mismatch has been reported at the level of the trochlea, anterior chamfer, and distal cut[1, 2], which led to gradual improvements in implant design[4-6]. Conversely, prosthetic overhang at the posterior condyles is rarely reported, and its incidence and consequences are ill-understood. Barnes and Scott[7] described femoro-popliteal impingement after TKA due to prosthetic overhang at the posterior aspect of the lateral condyle. More recently, high incidences of posterolateral overhang were observed in Japanese[8] and Indian[9] populations, leading authors to suggest modifications in this specific zone of knee implants.

Most morphometric studies on the posterior condyles focused on sagittal radii of curvature[10-14] or widths measured on a single transverse plane without considering three-dimensional asymmetry[15, 16]. Whether the posterior condyles are symmetric or asymmetric, and whether they are matched by the symmetric condyles of most commercially available implants, remain unanswered questions.

External rotation of the femoral component is frequently performed in TKA to improve ligament balancing[17], patellofemoral tracking, and flexion kinematics[10, 18-20]. The resulting modification of the posterior cut influences the dimensions and asymmetry of the resected condyles[16, 21]. Recently, Minoda et al described two main types of posterior cutting guides, depending on the way the rotation is applied[21]. With 'central-referencing' guides, the rotation is performed around the intercondylar notch, resulting in both medial over-resection and lateral under-resection. With 'medial-referencing' guides, the rotation is performed around the medial condyle, resulting mainly in lateral under-resection[22-24] (Figure 1).

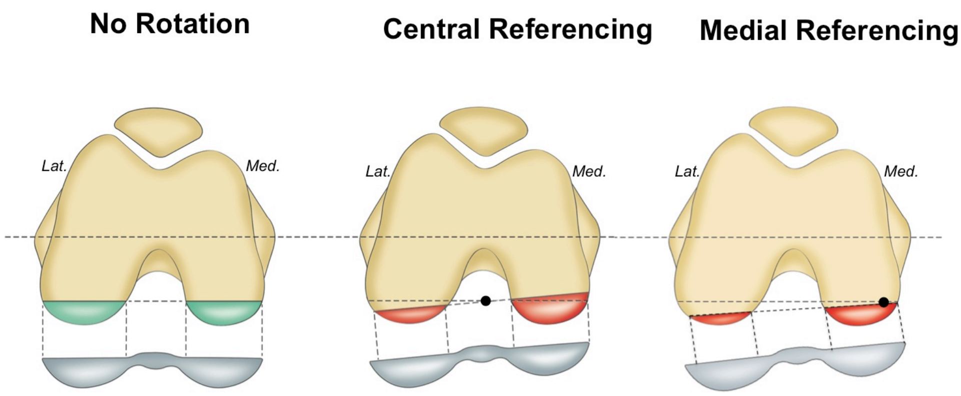

Figure 1: External rotation of the femoral component requires modification of the posterior cut and influences the dimensions and asymmetry of the resected posterior condyles. With 'central-referencing' guides, the rotation is performed around the intercondylar notch, resulting in both medial over-resection and lateral under-resection. With 'medial-referencing' guides, the rotation is performed around the medial condyle, resulting mainly in lateral under-resection.

To our knowledge, the shape and asymmetry of the posterior condyles were never precisely investigated and compared to TKA implants. The present study therefore aimed to (i) investigate the mediolateral and proximodistal dimensions of the femoral condyles in arthritic knees, to enable precise quantification of condylar asymmetry on the posterior resection plane, (ii) quantify the influence of external rotation of the femoral component on asymmetry of the posterior condyles and (iii) compare anatomic measurements to the corresponding dimensions of commercially available implants. Our hypotheses were that, at the posterior resection plane, the lateral condyle is narrower than the medial condyle, and that external rotation considerably exaggerates this asymmetry.

Patients and Methods

A consecutive series of 114 knees (63 females and 51 males) in 112 patients that underwent primary TKA between January 2008 and June 2009 by the senior surgeon (MB) was retrospectively analyzed. A computed tomography (CT) scan is performed as part of a routine preoperative planning for TKA at our institution. The series excludes patients with previous surgery or trauma or with an unclear CT scan due to artefacts from surrounding metal or contrast agent. The mean age of the patients was 72 years (range; 56 to 88), mean weight was 81 kg (range; 45 to 125) and mean height was 168 cm (range 144 to 194). The indication for TKA was osteoarthritis OA in 110 knees and spontaneous necrosis of the medial condyle in four. OA was restricted to the medial compartment in 81 knees, to the lateral compartment in 15 knees, the patellofemoral joint in six, and was bi-compartmental in eight. Preoperative long-leg radiographs were available for 107 knees. In these knees, the mean tibiofemoral angle (TFA) was 176° (range 160° to 194°). A total of 80 knees had varus alignment with a TFA angle <180° and 27 knees had valgus alignment with a TFA angle >180°.

CT scans were performed with an identical protocol in all patients using a 64-slice multidetector scanner (Siemens® Sensation, Munich, Germany) in the supine position with the knees fully extended and the legs fixed in neutral rotation. The knee was scanned from 50 mm above the superior patellar margin to the inferior aspect of the tibial tuberosity. DICOM images were processed using OsiriX (Pixmeo SARL, Bernex, Switzerland)[25, 26]. This imaging software enabled simultaneous visualization of CT cross-sections in the frontal, sagittal and transverse plane. Whereas the software enables direct measurement of dimensions and angles in all three planes, it only permits consistent exportation of three-dimensional (3D) coordinates digitized on the native transverse CT slices. Therefore, to view and measure dimensions in the frontal plane, it was necessary to first digitize femoral contours on each transverse CT slice, taking care to circumvent osteophytes, and then export them to spreadsheets for further processing in Excel (Microsoft Corp., Redmond, USA). The native transverse slices were assumed to be orthogonal to the femoral mechanical axis, within ±10º of error, hence there were taken to be negligible errors owing to malalignment of the femur within the scanner (maximum error = 1- cos 10º = 1.5%).

The reference plane corresponded to the standard femoral posterior resection plane in TKA without applying any external rotation (neutral position). It represented the posterior condyles in the coronal view 10mm anterior to the posterior bicondylar line (Figure 2). Mathematical matrices were then applied to externally rotate the reference section by 3º and 5º around: (i) the centre of the intercondylar notch (central referencing) and (ii) the centre of the medial condyle (medial referencing). The maximal height and width of each condyle were measured in neutral position and in each of the four additional rotated planes. The total width of the femur at the theoretical distal resection level, 10mm proximal to the most distal condyle, was also measured (Figure 3). The height and width of the condyles were represented both as absolute values and as asymmetry ratios, comparing the dimensions of the lateral condyle to the corresponding dimensions of the medial condyle. The width of each condyle was also represented as a ratio in relation to the total width of the femur (width-ratio = total width of the femur / width of the posterior condyle).

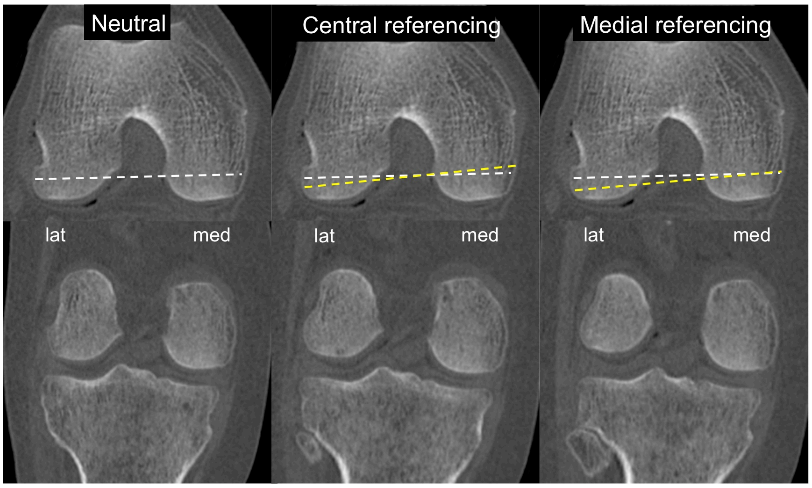

Figure 2: Transverse (top) and coronal (bottom) views of the distal femur, illustrating the femoral posterior resection plane. Left column: the posterior cut is in neutral position (white dashed line), 10mm anterior and parallel to the posterior bicondylar line. Middle column: external rotation applied by 'central referencing' (yellow dashed line). Right column: the same amount of external rotation applied by 'medial referencing' (yellow dashed line).

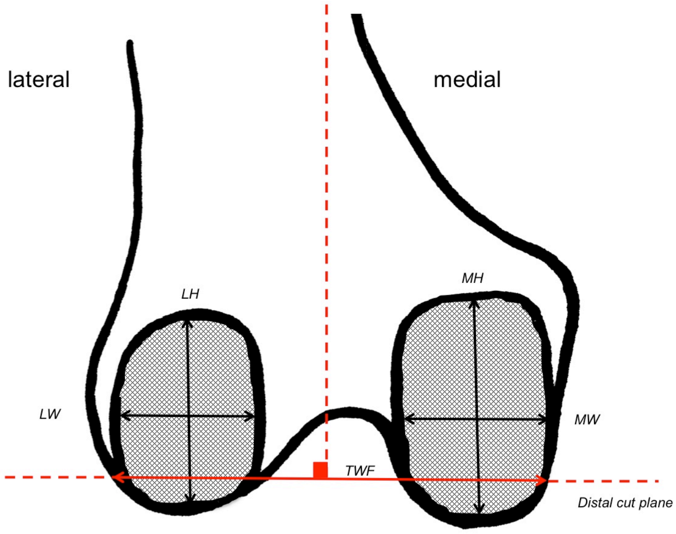

Figure 3: The height and width of the medial and lateral condyles measured at the posterior resection plane. The total width of the femur (TWF) was measured at the level of the distal cut. *LH: lateral condyle height, LW: lateral condyle width, MH: medial condyle height, MW: medial condyle width.*

We formed a sample of 13 explanted femoral components and identified each specimen by its laser marking to determine its manufacture, model, serial number, size, and side. The specimens were scanned using a 3D optical scanning machine (ATOS II, GOM mbH, Braunschweig, Germany) and its photogrammetic analysis software (TRITOP, GOM mbH, Braunschweig, Germany). The system has a resolution of measurement of 0.05 mm and overall accuracy of ± 0.01 mm. The 3D reconstructions of the specimens were manipulated using ProEngineer software (ProEngineer, Needham, Massachusetts) to calculate the equivalent heights and widths dimensions as those recorded from the CT scans of the patients. The study had ethical approval and all patients gave informed consent.

Statistical analysis

The Student t-Test was used to verify significance in differences (dimensions and ratios) between medial or lateral condyles, and between males or females. Statistical analysis was performed using Excel (Microsoft Corp., Redmond, USA).

Results

In the neutral position, the dimensions of the medial and lateral condyles were nearly equal, with average differences <1mm. Externally rotating the posterior cut induced asymmetries that increased with rotation angle, and were exacerbated using ‘medial referencing’ compared to ‘central referencing’ (Figure 4). The lateral/medial asymmetry ratios were 0.92 to 0.96 with 3° of rotation, and 0.85 to 0.94 with 5º of rotation (Table 1).

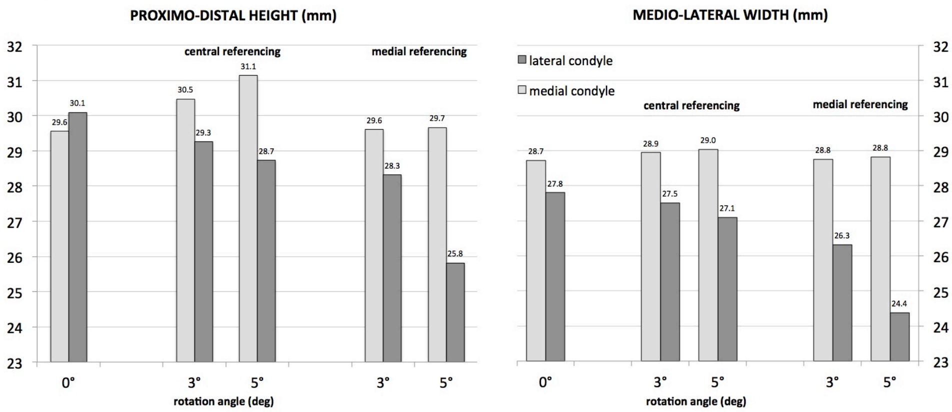

Figure 4: Dimensions of the medial and lateral condyles (vertical axis, mm) in neutral position (0º of rotation) and at 3º and 5º of external rotation, using ‘central referencing’ and ‘medial referencing’ techniques.

With ‘central referencing’ rotations, the height increased for the medial condyle and decreased proportionally for the lateral condyle. The width remained nearly constant for the medial condyle but decreased slightly for the lateral condyle (Figure 5). The difference in heights between the medial and lateral condyles was 1.1mm SD 2.3 (-3.0 to 10.0) at 3° of rotation, and 2.3mm SD 2.3 (-3.0 to 8.0) at 5° of rotation. The difference in widths between the medial and lateral condyles was 1.4mm SD 2.0 (-4.4 to 6.5) at 3° of rotation, and 1.8mm SD 2.2 (-4.6 to 8.2) at 5° of rotation. The distribution of measurements reveals that externally rotating the femoral cut by 5º induces height asymmetry >3 mm in 46%, and width asymmetry >3mm in 32% (Figure 6).

Table 1: Dimensions of the posterior condyles at the posterior resection plane

		Medial condyle mean ± SD	Medial condyle (range)	Lateral condyle mean ± SD	Lateral condyle (range)	*p-value*[1]	Ratio (Lateral / Medial) mean ± SD	Ratio (Lateral / Medial) (range)	*p-value*[2]
Proximo-distal height									
neutral position	0˚	29.6 ± 3.15	(22.0 – 44.0)	30.1 ± 2.97	(22.0 – 40.0)	0.012	1.02 ± 0.08	(0.81 – 1.22)	
central reference	3˚	30.5 ± 3.44	(22.0 – 44.0)	29.3 ± 3.17	(18.0 – 42.0)	<0.001	0.96 ± 0.08	(0.64 – 1.11)	<0.001
	5˚	31.1 ± 3.29	(24.0 – 42.0)	28.7 ± 2.98	(20.0 – 40.0)	<0.001	0.93 ± 0.07	(0.75 – 1.11)	<0.001
medial reference	3˚	29.6 ± 3.07	(22.0 – 44.0)	28.3 ± 2.98	(20.0 – 40.0)	<0.001	0.96 ± 0.08	(0.75 – 1.14)	<0.001
	5˚	29.7 ± 3.10	(22.0 – 44.0)	25.8 ± 3.19	(20.0 – 40.0)	<0.001	0.87 ± 0.09	(0.69 – 1.20)	<0.001
Medio-lateral width									
neutral position	0˚	28.7 ± 2.90	(22.9 - 35.9)	27.8 ± 2.83	(21.5 – 34.3)	0.012	0.97 ± 0.07	(0.75 – 1.16)	
central reference	3˚	28.9 ± 2.91	(23.1 - 36.6)	27.5 ± 2.82	(21.9 – 33.9)	<0.001	0.95 ± 0.07	(0.79 – 1.16)	<0.001
	5˚	29.0 ± 3.02	(22.5 - 36.7)	27.1 ± 2.77	(22.0 – 33.4)	<0.001	0.94 ± 0.07	(0.74 – 1.17)	<0.001
medial reference	3˚	28.8 ± 2.81	(22.1 - 35.7)	26.3 ± 2.67	(21.6 – 33.9)	<0.001	0.92 ± 0.08	(0.72 – 1.22)	<0.001
	5˚	28.8 ± 2.79	(22.1 - 35.7)	24.4 ± 2.66	(18.7 – 33.4)	<0.001	0.85 ± 0.09	(0.65 – 1.06)	<0.001

[1] differences in dimensions of medial condyle versus lateral condyle
[2] differences in ratios measured with rotations versus neutral position

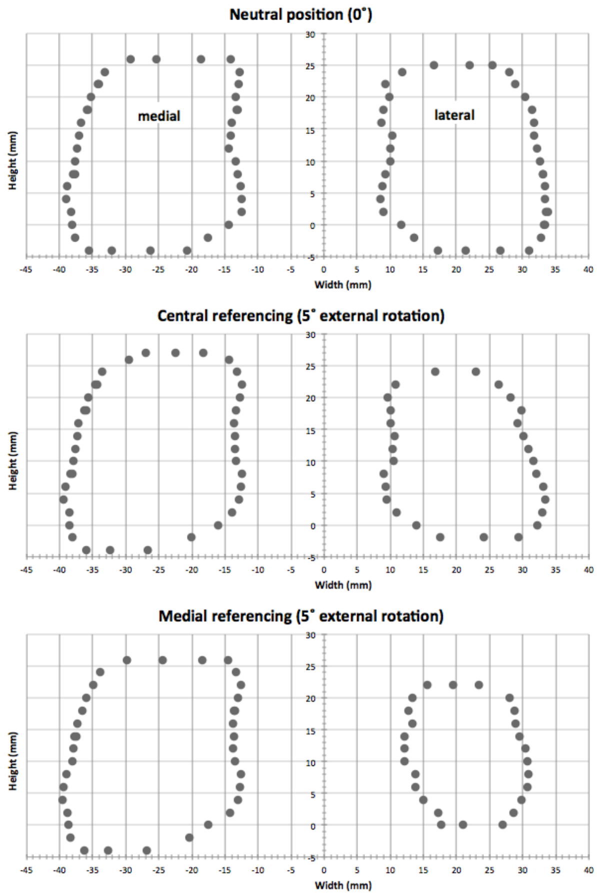

Figure 5: Digitized points as seen in the coronal view at the posterior resection plane, showing changes in shapes and dimensions of both condyles, when externally rotating the resection plane by 5º using 'central referencing' and 'medial

With 'medial referencing' rotations, the dimensions remained unchanged for the medial condyle, but decreased substantially for the lateral condyle. The difference in heights between the medial and lateral condyles was 1.3mm SD 2.4 (-4.0 to 9.0) at 3° of rotation, and 3.8mm SD 2.8 (-6.0 to 10.0) at 5° of rotation. The difference in widths between the medial and lateral condyles was 2.4mm SD 2.3 (-5.9 to 8.5) at 3° of rotation, and 4.4mm SD 2.7 (-1.5 to 11.9) at 5° of rotation. The distribution of measurements reveals that externally rotating the femoral cut by 5º induces height asymmetry >3 mm in 66%, and width asymmetry >3mm in 69% (Figure 6).

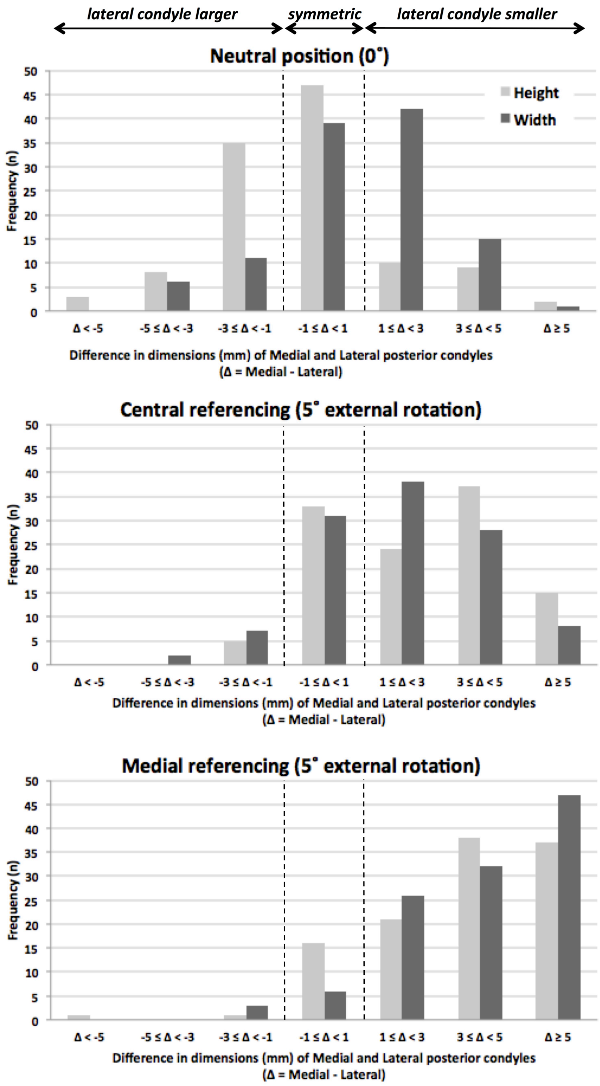

Figure 6: Distributions of condylar asymmetry (medial minus lateral, mm) in neutral position and at 5º of external rotation, applied by 'central referencing' and 'medial referencing' techniques.

The patterns and extents of asymmetries induced by externally rotating the posterior femoral cut were identical for both genders. While absolute dimensions were significantly greater in men than in women, the lateral/medial asymmetry ratios were nearly equal (Table 2). The patterns and extents of asymmetries were also similar for knees with varus or valgus deformity, as the lateral/medial asymmetry ratios were nearly identical for the different aetiology groups (Figure 7).

Table 2: Dimensions and ratios of the posterior condyles for males and females

			Males mean ± SD	Males (range)	Females mean ± SD	Females (range)	*p-value*
Proximo-distal height							
Dimensions (mm)	medial condyle	0°	31.0 ± 3.36	(24.0 – 44.0)	28.4 ± 2.43	(22.0 – 36.0)	<0.001
	lateral condyle	0°	31.6 ± 2.95	(24.0 – 40.0)	28.9 ± 2.39	(22.0 – 34.0)	<0.001
Ratios (Lateral/Medial)	neutral position	0°	1.02 ± 0.08	(0.81 - 1.22)	1.02 ± 0.07	(0.81 - 1.18)	0.861
	central reference	3°	0.96 ± 0.07	(0.80 - 1.11)	0.97 ± 0.08	(0.64 - 1.08)	0.590
		5°	0.93 ± 0.08	(0.75 - 1.11)	0.92 ± 0.07	(0.77 - 1.08)	0.658
	medial reference	3°	0.96 ± 0.08	(0.75 - 1.11)	0.96 ± 0.08	(0.75 - 1.14)	0.994
		5°	0.85 ± 0.10	(0.69 - 1.20)	0.89 ± 0.07	(0.73 - 1.08)	0.023
Medio-lateral width							
Dimensions (mm)	medial condyle	0°	30.6 ± 2.52	(23.1 – 35.9)	27.2 ± 2.26	(22.9 – 33.5)	<0.001
	lateral condyle	0°	29.9 ± 2.14	(25.5 – 34.3)	26.1 ± 2.15	(21.5 – 32.8)	<0.001
Ratios (Lateral/Medial)	neutral position	0°	0.98 ± 0.06	(0.87 - 1.15)	0.96 ± 0.08	(0.75 - 1.16)	0.224
	central reference	3°	0.96 ± 0.06	(0.80 - 1.08)	0.95 ± 0.08	(0.79 - 1.16)	0.274
		5°	0.93 ± 0.07	(0.74 - 1.07)	0.94 ± 0.08	(0.77 - 1.17)	0.795
	medial reference	3°	0.92 ± 0.07	(0.75 - 1.08)	0.92 ± 0.09	(0.72 - 1.22)	0.964
		5°	0.84 ± 0.09	(0.65 - 1.06)	0.86 ± 0.08	(0.67 - 1.06)	0.233

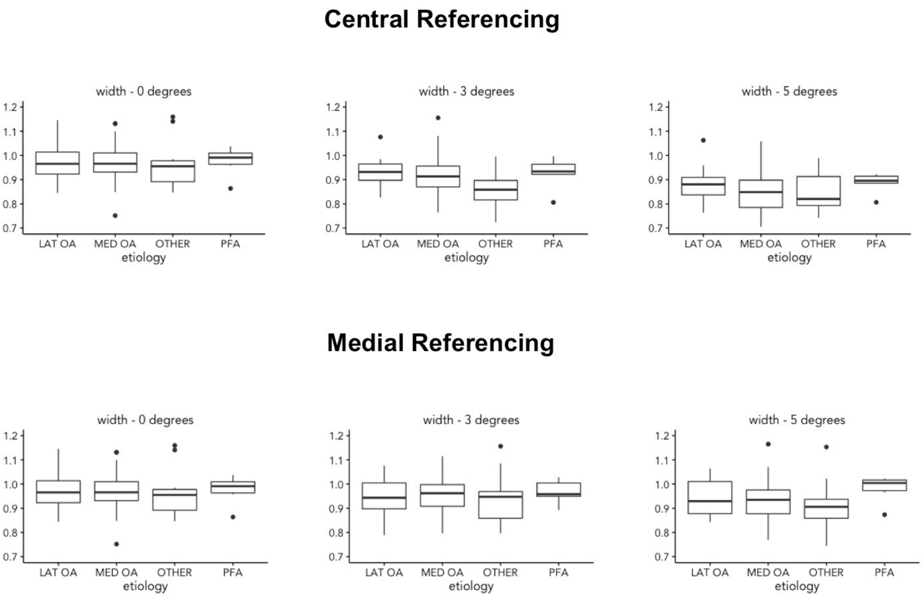

Figure 7: Boxplots illustrating asymmetry ratios of condylar width (lateral / medial) for the different aetiology groups.

From the 13 femoral components measured, 10 models had symmetric condyles with equal dimensions on the medial and lateral sides, while 3 models had a minor 'reversed asymmetry' with the lateral condyle slightly wider than the medial condyle. Comparing the width ratios (condyles/total femur) suggests that externally rotating femoral components with 'central referencing' guides would results in little or no prosthetic overhang at the lateral condyle, while with 'medial referencing' it would produce more pronounced prosthetic overhang at the lateral condyle, particularly if the rotation angle exceeds 3º (Figure 8).

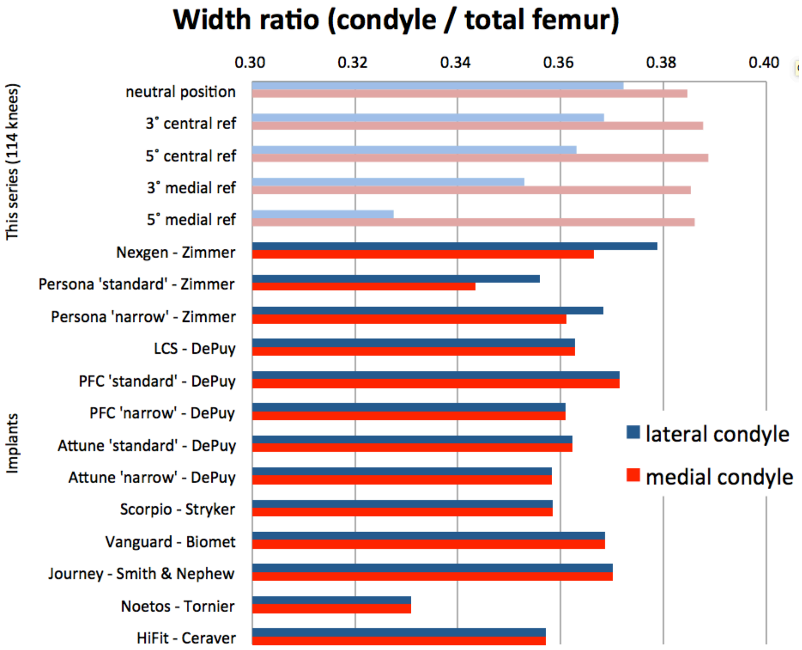

Figure 8: Comparison between dimensions of medial and lateral condyles relative to the total femur width in patients with those of 13 different TKA models.

Discussion

This study reveals that the posterior femoral condyles are generally symmetric in the neutral position but that externally rotating the posterior femoral cut induces some asymmetry, the extent of which depends on the rotation angle and referencing system. This phenomenon cannot be neglected, as dimensional differences up to 12mm were observed in some knees, with 5º of external rotation using medial referencing. The effects of this asymmetry could be prosthetic overhang at the lateral condyle and/or under-coverage at the medial condyle, particularly when using medial-referencing guides, which result in minimal lateral resection.

The influence of external rotation on the dimensions of the posterior resection was previously investigated by Poilvache et al.[16] who reported a thickness of 7.1mm at the lateral condyle compared to 9.8mm at the medial condyle, when the posterior femoral cut was parallel to the transepicondylar axis. Recently, Minoda et al.[21] reported up to 6.3mm differences in thickness of resected bone using central- versus medial- referencing guides, when applying 6° of external rotation. However, none of these authors studied the influence of this asymmetry on the mediolateral and proximodistal dimensions of the resected surfaces, and the subsequent risks of posterior prosthetic overhang.

Stating that condylar asymmetry leads systematically to a posterolateral overhang would be an over simplification, as there are several surgical factors and design features that could counterbalance this mismatch, such as femoral component mediolateral positioning, sizing and varus-valgus alignment. Consequences of condylar asymmetry could also be under-coverage of the medial condyle, as well as prosthetic overhang within the intercondylar notch. Implant sizing in TKA requires consideration of multiple interrelated factors, and surgeons frequently accept slight distal under-coverage to avoid soft-tissue impingements[1]. Anyway, our data demonstrate that the dimensions of prosthetic posterior condyles are more adapted to the medial than to the lateral condyle, and surgeons should be aware of that.

This study has several limitations: First, the patients were all Caucasians, and morphologic characteristics cannot be extended to Asian or African populations. Second, measurements were made on arthritic knees, which may be deformed by the pathologic process. Third, dimensions were measured only at the posterior resection plane, in terms of width and height, without considering the exact shape or volume of bone removed. Finally, distinguishing native cortical contours from osteophytes was done manually and this might have altered the precision. The study has numerous strengths, however, notably the measurement protocol developed which enabled reliable simulation of two rotation angles, using two reference systems, and the use of CT scans that permitted precise measurements, and exploration of an area that is difficult to access or visualise intraoperatively or using other imaging modalities. Direct measurements of the removed resected condyles[16] are imprecise due to oscillating saw thicknesses, possible fragmentation of resections, and lack of repeatability in the zone of measurement. Such technical difficulties could explain why the morphology of the posterior condyles has been so poorly studied. In 1987, Yoshioka et al. performed a meticulous radiographic study of the distal femur, but did not quantify the dimensions of the posterior medial and lateral condyles[10]. Nearly a decade later, Poilvache et al. published a detailed morphometric analysis from intra-operative bone resections, but did not quantify the widths of the posterior resections[16]. Recently Monk[15] analyzed a series of MRI from 25 healthy volunteers and demonstrated that the postero-lateral condyle was narrower than the postero-medial condyle[15], though these measurements were taken at the margin of the articular cartilage rather than at the level of bone resections needed for TKA.

The real incidence of prosthetic overhangs at the posterior condyles is rarely reported and probably underestimated due to the difficulties to visualize precisely in vivo the contours of the chromium-cobalt implant with respect to the bony contours. Furthermore, surgeons rarely consider bone-implant fit at the posterior condyles, which are difficult to visualize and because mediolateral positioning and sizing are mostly adapted to the distal fit. While Barnes and Scott reported popliteus impingement with an overhanging metallic posterior condyle in 2.7% of their patients, Mahoney et al.[2] investigated femoral oversizing but did not report overhang at the posterior condyles specifically, though all knees were operated through a subvastus approach which could have limited visibility of the posterolateral area. Two recent studies on Asian populations, Hirakawa et al in Japan[8] and Shah et al in India[9], reported a rate of posterolateral overhangs of up to 62.5% after TKA and concluded that prosthetic condyles should be redesigned. The clinical consequences of such posterolateral overhangs are not well documented, but impingements with soft tissues – mainly the popliteus tendon or the posterolateral capsule – could explain residual pain or stiffness[27, 28].

External rotation of the femoral component in TKA is widely accepted but there is no consensus on the two principal technique and associated landmarks[29]. In the measured-resection technique, the desired rotation angle is applied using the cutting guide with either central- or medial-referencing[21]. In the tension-gap technique, the external rotation is adapted to the flexion gap, and by default tends towards medial-referencing[24, 30, 31]. The goal of the present study was not to demonstrate superiority of one technique over the other, as both have advantages and disadvantages[29], but to highlight the possible consequences of asymmetric condylar resections. This study demonstrates that even if the medial-referencing rotation technique may help to improve ligament balancing in flexion, particularly in valgus knees[24, 32], it may lead to excessive asymmetry in the posterior condyle resection and can therefore result in posterolateral overhang.

Our data shows no differences in condylar asymmetry between varus and valgus knees. This contra-intuitive finding is probably because the virtual resections were referenced from the posterior condylar line, but did not take into account the transepicondylar axis[17, 33, 34]. In valgus knees, the posterior condylar angle is generally greater, requiring a more externally rotated cut[34-36].

Conclusions

Surgeons must be aware of prosthetic overhang that could arise in TKA particularly the posterior condyles region, which is least visible during surgery. Such overhangs could induce impingement against soft tissues, such as the popliteus tendon or the joint capsule, especially in deeper flexion angles. While the recommendation of externally rotating femoral components may be beneficial to optimize tibio-femoral and patello-femoral kinematics, it amplifies the perceived asymmetry between medial and lateral condyles, and therefore exacerbates prosthetic overhang particularly in the supero-lateral zone.

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Section III

The soft-tissues around the implants

9. Anatomy of the popliteus tendon and its interactions with TKA

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Abstract

Among all the soft tissue surrounding the knee joint, the popliteus tendon (popliteus) is of special interest due to its intra-articular situation and its intimate relationships with the articular surfaces, either at the tibia and femur level[1, 2]. After TKA, the popliteus is potentially vulnerable particularly in case of prosthetic overhang but its interactions with the new prosthetic contours are ill-understood.

Anatomy of the popliteus tendon

The close relationships between the popliteus and the bony surfaces of the knee have been well described. In a healthy knee, the lateral plateau is convex in the sagittal plane (Figure 1) and the popliteus remains in close contact with its posterolateral sloped surface (Figure 2 and 3). When crossing the popliteus hiatus, the popliteomeniscal fascicles and the popliteofibular ligament stabilize the tendon (Figure 4 and 5). Proximally, it crosses the lateral margin of the lateral condyle and inserts just distal and anterior or slightly posterior to the lateral epicondyle and distal to the insertion of the lateral collateral ligament (LCL)[1, 3, 4].

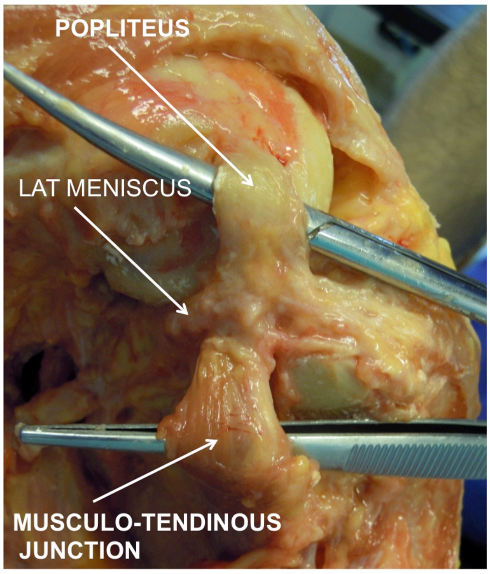

Figure 1: Dissection of the popliteus tendon from muculo-tendinous junction to femoral attachment.

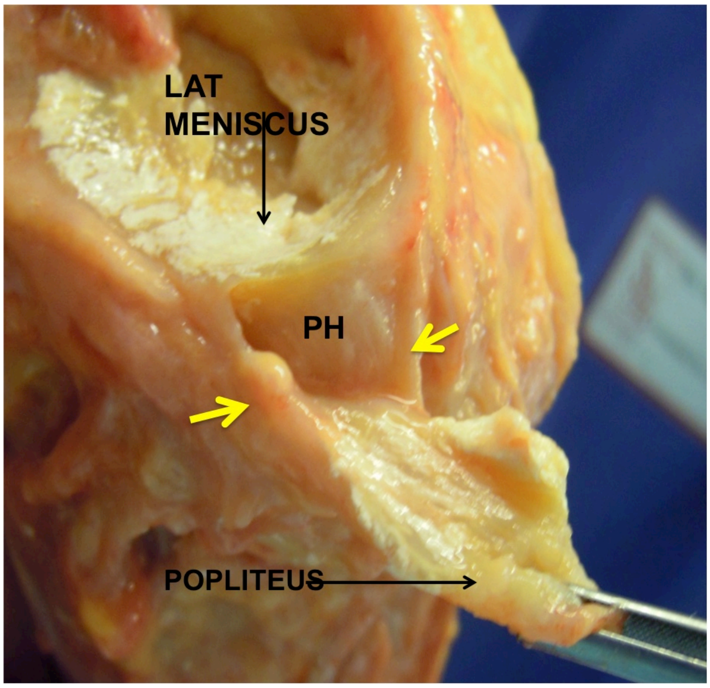

Figure 2: Posterolateral corner of a right knee view from above. The popliteus tendon is reclined laterally and the femur has been removed. (PH: Politeus hiatus; Yellow arrows: popliteomeniscal fascicles).

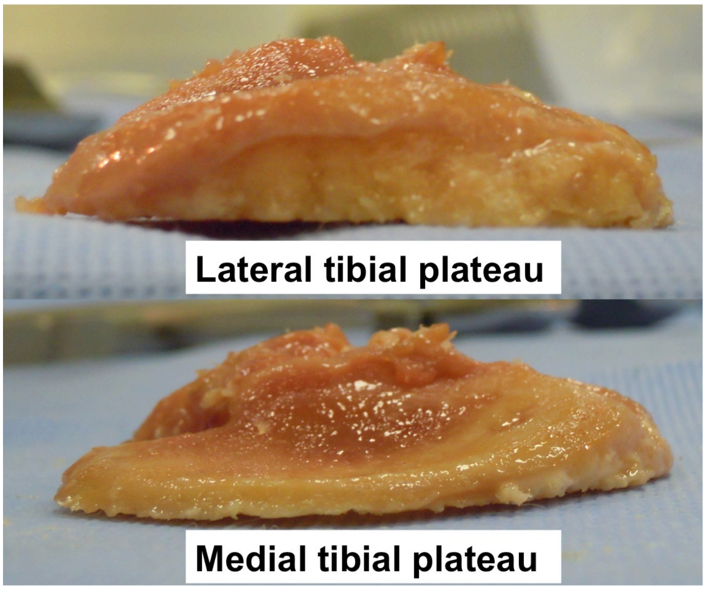

Figure 3: Lateral views of resected tibial plateaus during TKA. The lateral plateau (top) is convex while the medial plateau (bottom) is concave.

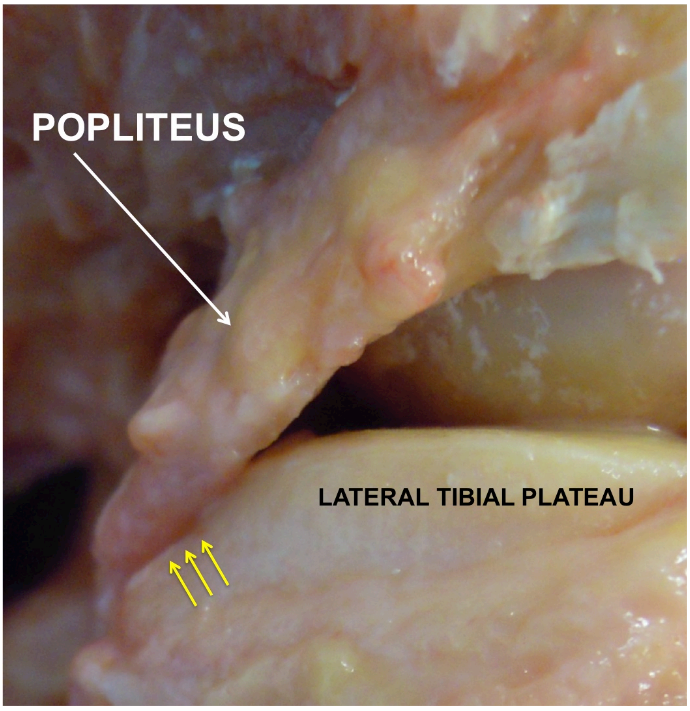

Figure 4: Lateral view of the popliteus tendon during cadaveric dissection. The lateral meniscus is removed. The contact between the popliteus and the postero-lateral corner of the plateau is visible (yellow arrows)

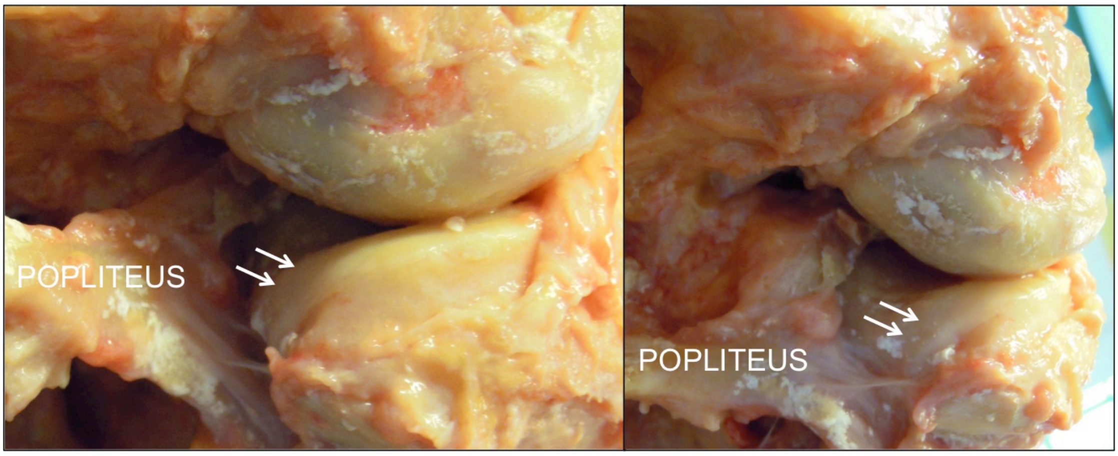

Figure 5:. Lateral (left) and postero-lateral (right) views of the popliteus tendon during cadaveric dissection. The tendon is posteriorly reclined and the contact articular surface between the tendon and the plateau (white arrows) is visible.

When the knee is extended, the popliteus is engaged in a vertical indentation of the lateral condyle margin, situated at the level of the condylo-trochlear junction, named the Sulcus Statorius[4] (or Sulcus Statarius[29]). During knee flexion, the popliteus glides on the margin of the lateral condyle and becomes fully seated in the popliteus sulcus above 105°[1, 5] (Figure 6). There is no consensus concerning the role of the popliteus muscle-tendon unit on knee stability[2, 6-8]. LaPrade et al. emphasized its role and consider the popliteus as the 'fith-ligament of the knee'[7] and Ullrich et al. demonstrated the importance of the popliteomeniscal fascicles on the stability of the lateral meniscus[9]. However, Thaunat et al. demonstrated recently that the popliteus muscle-tendon unit was not a primary static stabilizer of the knee[8].

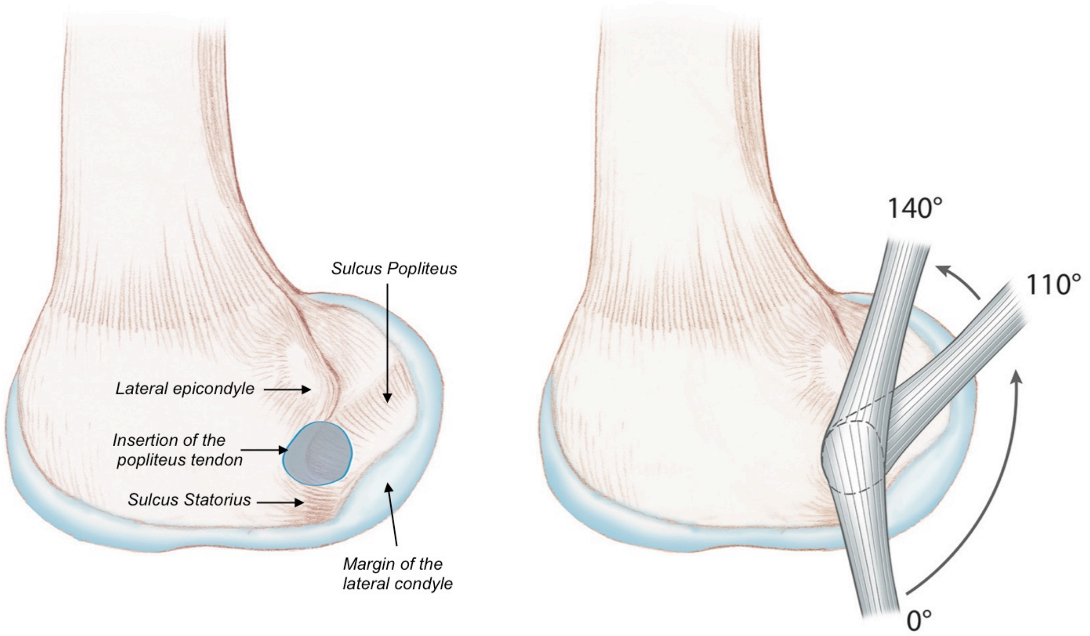

Figure 6: In native knees, the popliteus tendon inserts in an area located distal to the lateral epicondyle. In extension, the tendon is seated in the sulcus statorius. During flexion it glides along the margin of the lateral condyle and then seats in the popliteus sulcus beyond 100° of flexion.

Femoral insertion of the popliteus tendon

Several anatomic works have documented the insertion of the popliteus tendon and the anatomy of the popliteomeniscal fascicles. Brinkman et al., using an Isotrak digitizing device showed that the popliteus inserts 9.7 mm distal and 5.3 mm posterior to the lateral epicondyle and 11 mm distal and 0.84 mm anterior to the lateral collateral ligament (LCL) insertion, along a straight line, parallel to the long axis of the femur[3]. The mean surface area of its insertion is 65.9 mm^2 for Brinkman et al.[3] and 52.5mm^2 for Takeda et al.[10]. The insertion area is generally located in the anterior part of the popliteus sulcus, at an average distance of 12 mm (range 6 to 22 mm) from the distal articular margin[11] but many variations have been described[12].

The popliteus tendon is strongly attached to other posterolateral structures of the knee via the anteroinferior and posterosuperior popliteomeniscal fascicles attached respectively to the middle third of the lateral meniscus and the posterior horn of the lateral meniscus. The popliteofibular ligament is a complex structure, attached to the tibiofibular joint, to the fibular styloid and to the musculotendinous junction of the popliteus. An anterior division attaches also to the anteroinferior popliteomeniscal fascicle[2, 4, 13-15].

Phylogenetic origin of the popliteus tendon: from a 'third meniscus' to a tendon.

The specific intraarticular situation of the popliteus tendon is explained by its pylogenetic origin. In archaic species such as alligator, crocodiles and other reptiles, the body of the popliteus muscle inserts from the posterior aspect of the proximal tibia directly to the fibula. The head of the fibula articulates with the lateral and distal aspect of the lateral condyle, via a femoro-fibular meniscus, connected to the lateral femoral condyle by the femoro-fibular ligament (Figure 7)[2, 16-18].

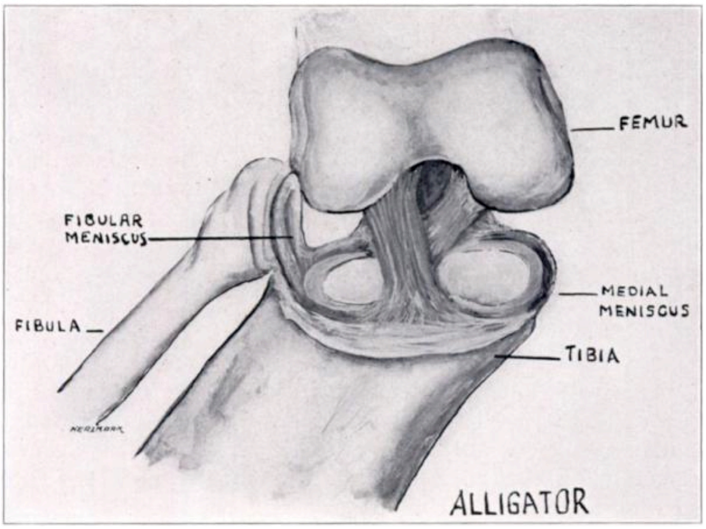

Figure 7: Representation of the alligator knee, showing the femoro-fibular meniscus.

From: Herzmark M, H (1938) The evolution of the knee joint. J Bone Joint Surg Am (20):77-84. With authorization.

This femoro-fibular joint allows movements of the fibular head with respect to the lateral condyle and rotation of the fibula around the tibia and therefore the rotational movements of the lower limb in reptiles. As demonstrated by Haines in 1942 this is quite similar to the ulna /radius rotation in the human forearm (Figure 8)[16]. This femoro-fibular joint can be seen in reptiles, birds and perhaps dinosaurs (Figure 9).

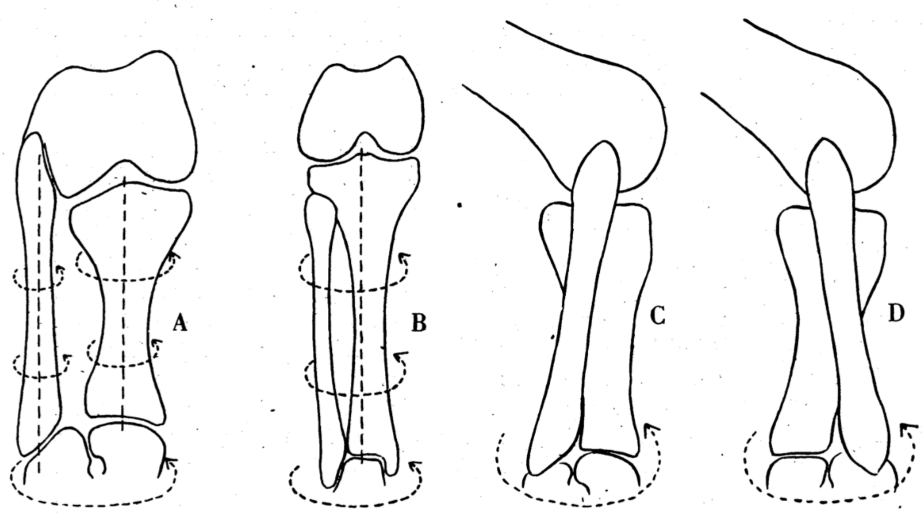

Figure 8: In archaic knees, (A,C,D) the rotation of the foot is obtained by a proximal rotation of the fibular head around the lateral condyle and a distal rotation between fibula, tibia and tarsus. In eutherian mamal knees (B), there is no mutual rotation between tibia and fibula.

From : Haines RW (1942) The tetrapod knee joint. J. Anat 76 (Pt 3):270-301.

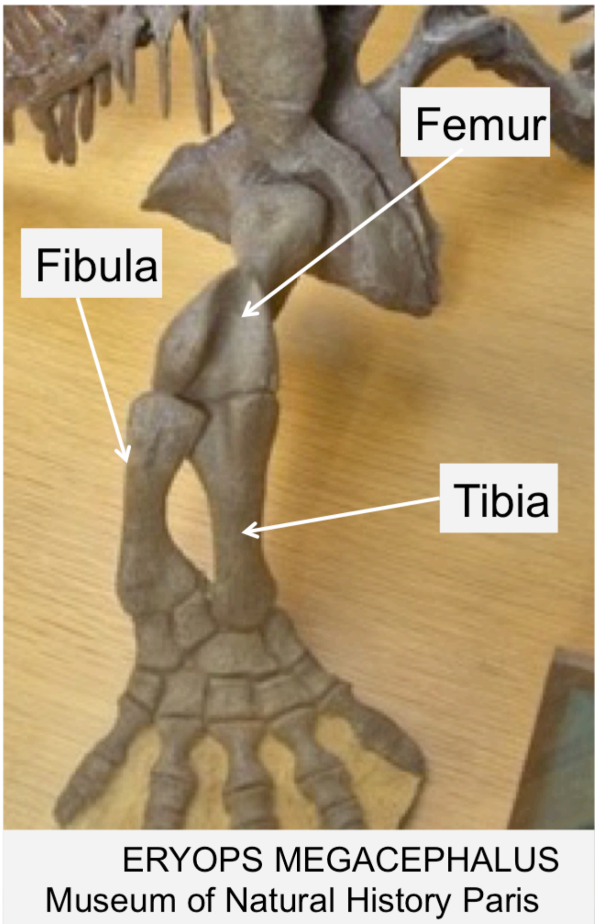

Figure 9 : Skeletton of a Eryops Megacephalus. The joint between the lateral condyle and the fibula is visible.

During the evolution of species, the fibula shortened progressively and the femoro-fibular meniscus, which remained attached to the fibular head, was stretched distally, attracted by the fibular head. Progressively attachments with the popliteus muscle developed and in placental (or eutherian) mammals, the popliteus tendon-muscle unit attached directly to the lateral condyle via the residual femoro-fibular meniscus (Figure 10). In early mammals such as the Opossum - a marsupial mammal - the fibular head is still above the joint line level in contact with the lateral condyle, but without cartilage[17].

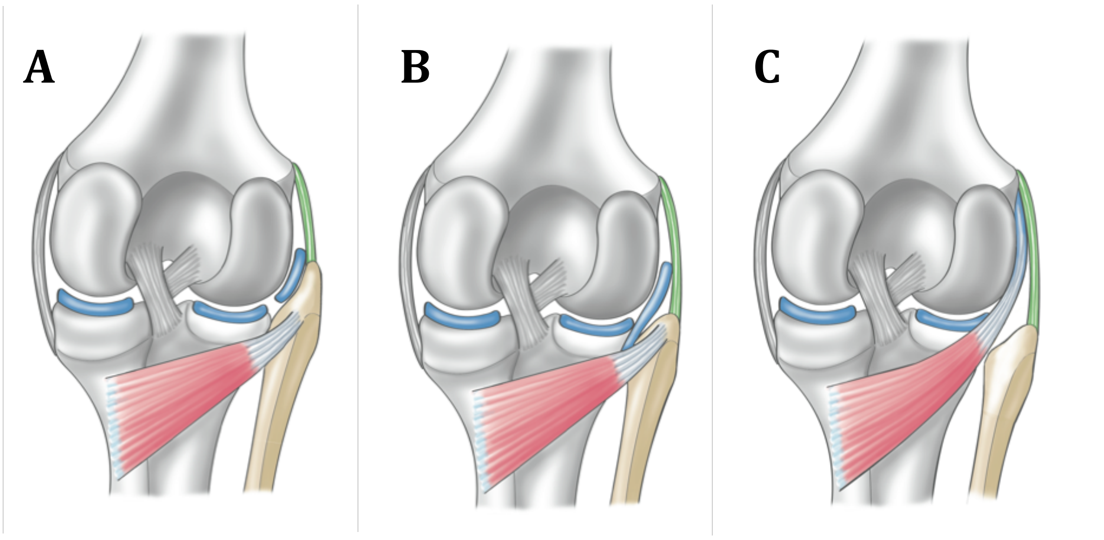

Figure 10 : Illustration of the evolution from reptils to mamals knees : In archaic knees (A), the fibular head articulates with the lateral condyle with a femoro-fibular meniscus (blue) and the popliteus muscle attaches on the fibula. Progressively (B) the fibula shortened attracting the femoro-fibular meniscus, which developped attachements with the popliteus muscle. Lastly (C) in eutherian mamals, the fusion of the femorfibular meniscus with the popliteus muscle formed the 'poplito muscle-tendon unit' with its intra-articular tendon.

Does TKA influences the tracking of the popliteus tendon?

The role of the popliteus in TKA stability is largely unknown. Kesman et al.[19] and Gosh et al.[20] investigated the influence of intraoperative section of the popliteus on knee laxity during implantation of a posterostabilized TKA. None of these authors observed increased laxity neither In Vitro[19, 20] nor In Vivo[19]. In a cadaveric study, Kanamiya et al.[21], Krackow et al.[22] and Matsueda et al.[23] demonstrated that, after TKA, the popliteus acts mostly as a secondary restraint and that an isolated section of the popliteus do not lead to laxity. On the other hand, De Simone et al.[24] observed in a retrospective study that patients with a iatrogenic non-treated intraoperative laceration of the popliteus tendon - reported on the surgical report - had lower knee society function score than a control group. Similarly, in an in vitro investigation, Cottino et al reported an increased TKA laxity after popliteus section, both with cruciate-retaining and postero-stabilized prosthesis[25].

Several authors described pain after TKA secondary to direct impingement between the prosthetic components and the popliteus. Barnes and Scott were the first to report a 'Femoro-Popliteal Impingement' due to an overhanging femoral component leading to residual pain in eight patients (Figure 11)[26]. Similarly, Allardyce and Scuderi have treated successfully with an arthroscopic section of the popliteus patients with residual lateral pain after TKA, suggesting a direct impingement as the cause of the pain[27]. Likewise, Kazakin and Nandi observed intraoperative snapping popliteus tendons during TKA[28].

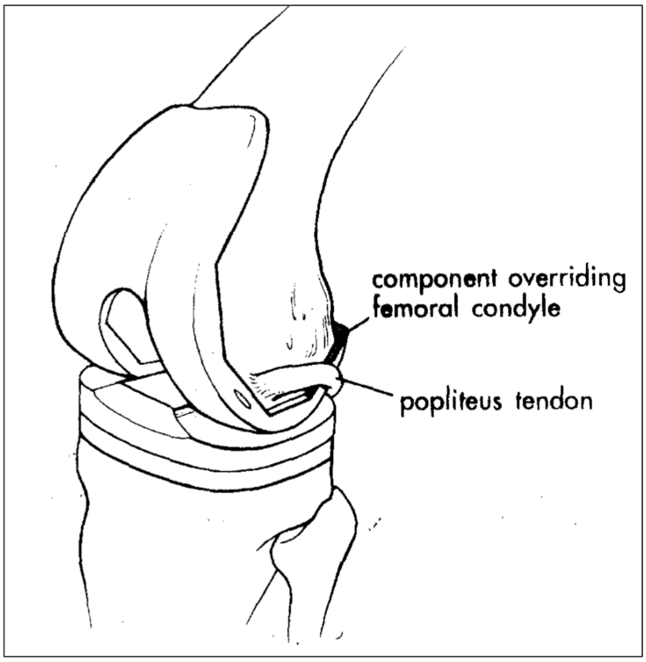

Fig 11 : Impingement between the popliteus tendon and an overhanging femoral component.

From Barnes CL, Scott RD (1995) Popliteus tendon dysfunction following total knee arthroplasty. J Arthroplasty 10 (4):543-545. With autorisation.

Conclusion

The unique situation of the popliteus tendon in the human body - intraarticular situation with a proximal bony insertion - is due to its phylogenetic meniscal origin. Due to its very intimate relationships with the bony contours, especially with the posterolateral tibial plateau and the margin of the lateral condyle, the popliteus is at high risk of impingement as soon as a prosthetic overhang occurs in one of these areas.

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10. Imaging the implant-soft tissue interactions in Total Knee Arthroplasty

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Abstract

Purpose: In Total Knee Arthroplasty (TKA), residual pain may be secondary to soft tissue impingements, which are difficult to visualize around chromium-cobalt implants using medical imaging, so their interactions remain poorly understood. The goal of this work was to establish a protocol for in-vitro imaging of the soft tissues around TKA, usable during throughout the range of motion (ROM).

Methods: The full size range of a commercially available TKA prosthesis was manufactured by 3D-printing in non-magnetic and non-radiopaque polymer and implanted in 12 cadaveric knees. The relations between these implants and the soft tissues (Popliteus tendon, Medial and Lateral Collateral Ligament, Patellar and Quadriceps tendons) were analyzed, using MRI (5 embalmed specimens) and CT scans after injection of the tissues with barium-sulfate (3 embalmed and 4 fresh-frozen specimens).

Results: Both MRI and CT scans enabled good identification of the soft tissues before TKA implantation. MRI produced minimal loss in signal and contrast, and neither the low temperature nor the embalming fluids compromised image quality. CT scans were more precise after TKA implantation, particularly the borders of the implant and the differentiation of soft tissues. Full ROM investigation, manual segmentation and three-dimensional reconstructions were possible only with the CT scan.

Conclusion: The experimental approach described in this study was successful in visualizing the interactions between the soft tissue and the implants before and after TKA and during the full ROM. The coordinate system allows to localize precisely the different anatomic structures and to quantify any change due to prosthetic implantation.

Introduction

In Total Knee Arthroplasty (TKA), residual pain and poor functional outcomes can be due to impingements between prosthetic components and soft tissues such as the Popliteus tendon (popliteus)[1, 2], the Patellar tendon (PT)[3], the iliotibial band (ITB)[4] or the Medial Collateral Ligament (MCL)[5, 6]. Impingements can be secondary to prosthetic overhang or component malposition[1, 2, 5-8] but may also occur in well-sized and well-positioned prostheses[7]. Optimizing bone-implant fit is therefore a concern for surgeons, engineers and manufacturers, and precise knowledge of the interactions between soft tissues, bone contours and prosthetic components during full range of movement would be useful.

In-vivo imaging of the soft tissues around metallic implants is challenging. Magnetic Resonance Imaging (MRI) allows high quality explorations if implants are made from non-magnetic alloys like titanium but it provides poor quality images with Chromium-Cobalt alloys, commonly used in TKA[9]. Even when using metal artifact reduction sequences (M.A.R.S.), soft tissue visualization around TKA remains of poor quality[10-12]. Recent investigations performed in specialized centers still report a lack of accuracy for visualization the soft tissue[13] and the polyethylene[14] after knee prostheses. Computed Tomography (CT) is widely used in patients with TKA, but does not enable accurate identification of soft tissues, particularly in the presence of metallic components due to scattering[15]. Ultrasonography can be used for clinical purposes and allows dynamic explorations but it is hardly used for precise anatomic investigations[16].

Cadaver dissections help to understand the relations between bone and soft tissues, but correct visualization requires aggressive dissections, which compromise the native anatomy and enable only qualitative assessments. The use of CT scans or MRI with cadaver specimens could avoid such large dissections and enable quantitative measurements of soft tissue displacements and impingements, but the above-mentioned difficulties with in-vivo MRI or CT scan persist.

The purpose of this work was to optimize a technique for in-vitro imaging of the soft tissues around TKA usable during the full range of motion. In order to circumvent the difficulties encountered with chromium-cobalt implants, we obtained from a manufacturer the full range of a commercially available prosthesis made from non-magnetic and non-radiopaque polymer. We analyzed the relations between these plastic implants and the surrounding soft tissues, using MRI and CT scan after cadaveric implantation. We compared the imaging technique depending on the radiological technique (MRI or CT scan) and the type of specimen (embalmed or fresh-frozen). We therefore asked several questions: Is it possible to obtain a good vision of the soft tissues around such plastic implants using standard imaging techniques? Which technique between MRI or CT scan provides the best quality images? Which preparation of specimens between embalmed or fresh-frozen provides the best images?

Material and methods

Twelve human cadavers donated for research by testament were used in this investigation and our institutional review board granted ethical approval for this study in advance (Reference number EC-2014/0847). None of the cadaver knees had history of previous surgery.

The investigation focused on the Popliteus Tendon (popliteus), the Lateral Collateral Ligament (LCL), the Medial Collateral Ligament (MCL), the Quadriceps Tendon (QT) and the Patellar tendon (PT). The ITB was excluded from this study due to technical difficulties outlined below. The visualization of these tissues was analyzed from full extension to maximum flexion. The implanted prosthesis was a copy of the HLS-KneeTech® (Tornier SA, Montbonnot, France) provided by the manufacturer and obtained using additive manufacturing technology with Fused Deposition Modeling FDM® using a Stratasys Dimension Elite™ (Eden Prairie, MN USA). The implants were made with a radio-opaque and non-magnetic polymer (Acrylonitrile butadiene styrene).

TKA implantation

The prosthesis was postero-stabilized, with eight sizes available for the tibial component and ten for the femoral component. Implantation was done through a medial parapatellar approach and the patella was not resurfaced. We used the standard conventional instrumentation obtained from the manufacturer. The tibial cut was orthogonal to tibial axis and was done first. On the femur, the posterior cut was aligned parallel to the transepicondylar axis, the distal cut was orthogonal to the femoral mechanical axis and a gap-balancing technique was used. Cementation was done with polyester free from barium sulfate (Polyester Demaere, Brussel, Belgium).

Imaging Techniques

Three different preparations and imaging techniques were used. In group I (5 knees), MRI was performed on cadavers embalmed with the Thiel technique[17, 18]. In group II (3 knees), CT scan analysis was also done on Thiel embalmed cadavers. In group III (4 knees), the CT scan was done on fresh frozen cadavers. The 12 cadaver specimens were initially intended to form 3 equal groups, but the challenges faced with MRI settings required the use of an additional specimen, which resulted in unequal group sizes. The embalmment technique described by Thiel in 1992[18] intended to preserve tissue flexibility and joint mobility compared to classic embalmment techniques using glutaraldehyde or formaldehyde[17], though the influence of the conductivity of the embalming fluids on the MRI signal and contrast remains controversial[19,20].

Group I - MRI imaging. MR imaging was performed on a 3T Magnet (Trio Tim, Siemens, Erlangen) with the body array. Imaging protocol consisted in a 3D TSE proton density weighted sequence (SPACE imaging) (TR : 1570, TE : 39). Images were obtained with a 0.5 mm section thickness, a 320x320 pixels matrix and a 15x15 cm Field of View. Due to the small diameter of the MRI tube, transections at the mid-shaft of the femur and the tibia were necessary to achieve full flexion of the knee. The knees were scanned in lateral decubitus position before and after TKA implantation, from full extension to full flexion in 20° increments between each position, measured with a goniometer. Particular attention was paid to maintain the room temperature at 20°C during the entire process[21].

Groups II and III - CT scan imaging. With this technique a contrast medium was injected in the soft tissues in a first step. The popliteus and the LCL were approached via a lateral incision. After incision of the iliotibial band, the popliteus and the LCL were identified. The QT and the PT were approached using a medial subvastus incision. The MCL was approached from the anterior skin incision after subcutaneous dissection. The superficial fibers of the MCL were exposed from their epicondylar insertion to their distal tibial insertion. After exposure, the contrast medium - a mixture of glycerol (70%) and barium sulfate (30%) - was injected in these tissues using a previously described technique[22]: A thin needle (0.45 mm x 23 mm) was inserted between the collagen fibers of the explored tissue, and the solution was injected with mild pressure until leakage occurred at the injection site. Pieces of gauze swabs were wrapped around adjacent structures in order to prevent contamination of possible leaking contrast solution. The injection needle was then directed towards the insertion sites until the contact point with the bony surface. On this spot, a small bolus of contrast was injected and this was repeated covering the complete insertion area[22]. It is worth noting that the ITB was inaccessible to this technique due to its thin structure.

The barium concentration had been determined during a prior investigation where different concentrations from 30% to 90% were tested, and 30% appeared to be optimal for good visualization with minimal scattering[22]. After injection, the skin and subcutaneous tissues were meticulously closed.

The knee was then scanned using a 64-slice multidetector CT scanner (Siemens Sensation, Munich, Germany). Scans were performed with the full body tilted in lateral decubitus using 0.6mm thick slices from extension to full flexion, by 20° increments controlled with a goniometer. The knee was scanned again with the same technique after TKA implantation.

Analysis of the DICOM images

DICOM images were analyzed using OsiriX® software (Pixmeo SARL, Bernex, Switzerland) with 3D multiplanar reconstructions. The quality of the images obtained in the three groups was compared using 10 criteria, taking account of the bone visualization, the capacity to investigate the full range of motion, the visualization of the implants and the visualization of the soft tissues in contact with the implants. The four medical doctors evaluated all images blindly (two senior orthopaedic surgeons, one resident orthopaedic surgeon, and one rheumatologist who independently ranked each criterion from 0 to 5.

Raw DICOM images were used to build three-dimensional reconstructions of bone, implants and soft tissues, using Mimics® software (Materialize®, Leuven, Belgium). First, Mimics®

automatically built the bone masks. Second, to improve the accuracy of implant visualization, the Stereolithography (STL) files (3D Systems, Rock Hill, South-Carolina USA) provided by the manufacturer were matched with the postoperative reconstructions (Figure 1). Third, the soft tissues were digitized by manual segmentation at each slice level (Figure 2). Fourth, coordinates of digitized points were exported to spreadsheets and processed using Matlab® (MathWorks®, Natick, MA, USA), in order to analyze the position of all studied tissues during knee flexion and to quantify the potential displacements due to prosthetic implantation.

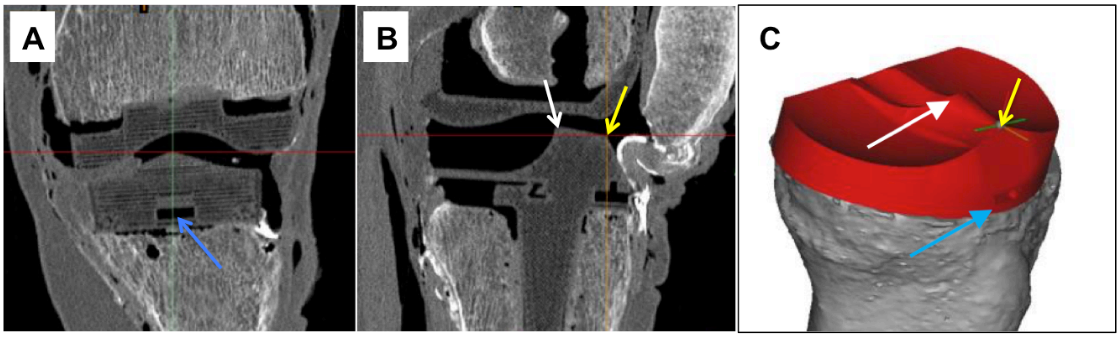

Figure 1: The STL files are imported in Mimics® and are fused with the raw images of the implants. Specific landmarks of the implants are used to do the manual fusion. On the tibia, three landmarks were used: (A) the anterior removal indentation of the polyethylene (blue arrow), (B) the most anterosuperior point of the polyethylene (yellow arrow), and the posterosuperior point of the cam (white arrow). The corresponding landmarks of the STL implant were then matched manually (C).

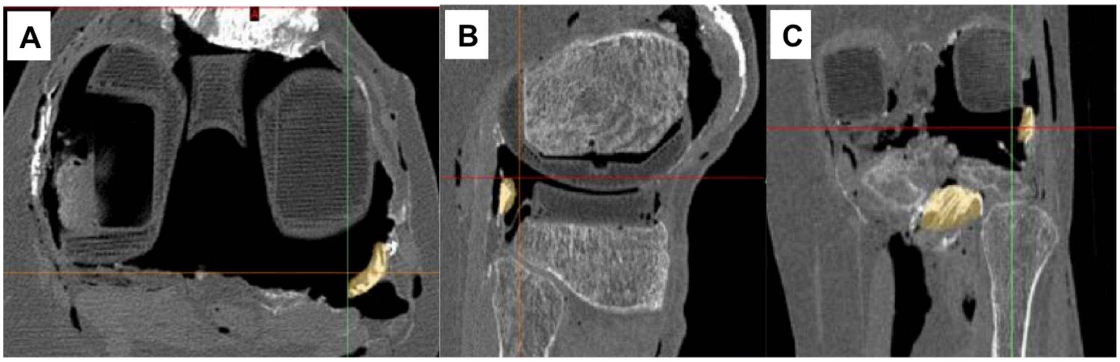

Figure 2: Segmentation of the soft tissues was done manually from the 3D multiplanar reconstructions. The popliteus tendon area is colored in yellow on the transverse (A), sagittal (B) and coronal (C) planes.

Statistical analysis

Statistical correlations and tests were not performed for this cadaveric imaging study as its results were chiefly qualitative and involved no population-based data.

Results

1- *Bone visualization*

Comparative analysis of the imaging obtained in the three groups is summarized in Table 1. With MRI only a minimal loss in signal and contrast was observed and neither the low temperature nor the Thiel embalming fluids seem to compromise the quality of the images. With CT scans, high quality images were obtained with a bony aspect close to what is observed in clinical practice. Interestingly, the quality of the images was similar when using Thiel embalmed and fresh cadavers (Figure 3).

Table 1: Comparison of the quality of the images obtained with the three protocols

	Evaluation (0 = worst, 5 = best)					
	MRI embalmed		**CT embalmed**		**CT fresh-frozen**	
	mean	range	mean	range	mean	range
Bone visualization						
Distinction of bone from soft tissues	2	(1 - 3)	3	(2 - 5)	4	(3 - 5)
Distinction cortical bone from cancellous bone	3	(2 - 4)	4	(2 - 5)	5	(5 - 5)
Similarity to conventional medical images	3	(2 - 4)	4	(2 - 5)	5	(5 - 5)
Prosthetic imaging						
Distinction of bone from implant material	1	(0 - 2)	4	(3 - 5)	4	(4 - 4)
Distinction of soft tissues from implant material	1	(0 - 2)	2	(1 - 3)	4	(4 - 4)
Soft tissue visualization						
Visibility of soft tissues along their entire length	3	(1 - 4)	3	(2 - 5)	3	(2 - 4)
Scattering / distortion	2	(1 - 3)	3	(2 - 5)	4	(4 - 4)
Range of motion						
Possibility to image the knee at all flexion angles	2	(0 - 3)	5	(5 - 5)	5	(5 - 5)
Mirroring / superposition	0	(0 - 0)	5	(5 - 5)	5	(5 - 5)
3D reconstructions						
Visibility of the entire knee	0	(0 - 0)	5	(5 - 5)	5	(5 - 5)
Total score	17		38		44	

Figure 3: Comparative aspect of the operated knee with MRI on embalmed specimen-group I (left), with CT scan on embalmed specimen-group II (middle) and with CT scan with fresh specimen-group III (right). This picture shows the raw images obtained with OsiriX®, in the transverse plane (A), the coronal plane (B) and the sagittal plane (C).

2- Prosthetic imaging

Both MRI and CT scan provided good quality images of the plastic components, without scattering. Prosthetic imaging was more precise with the CT scanner analysis, particularly the borders of the implant were easier to individualize. Fusion of the DICOM images with the STL files was only possible using the CT scans because of better visibility of prosthetic contours.

3- Soft tissue visualization

In the native knee, visualization of the soft tissues was better with the high definition MRI. However after prosthetic implantation, the differentiation between implant and soft tissue was always weak and segmentation appeared to be unreliable using MRI (Figure 4). Differentiation of soft tissues from the implants was better using CT scans on fresh frozen specimens, both at the femur (Figure 5) and the tibia (Figure 6).

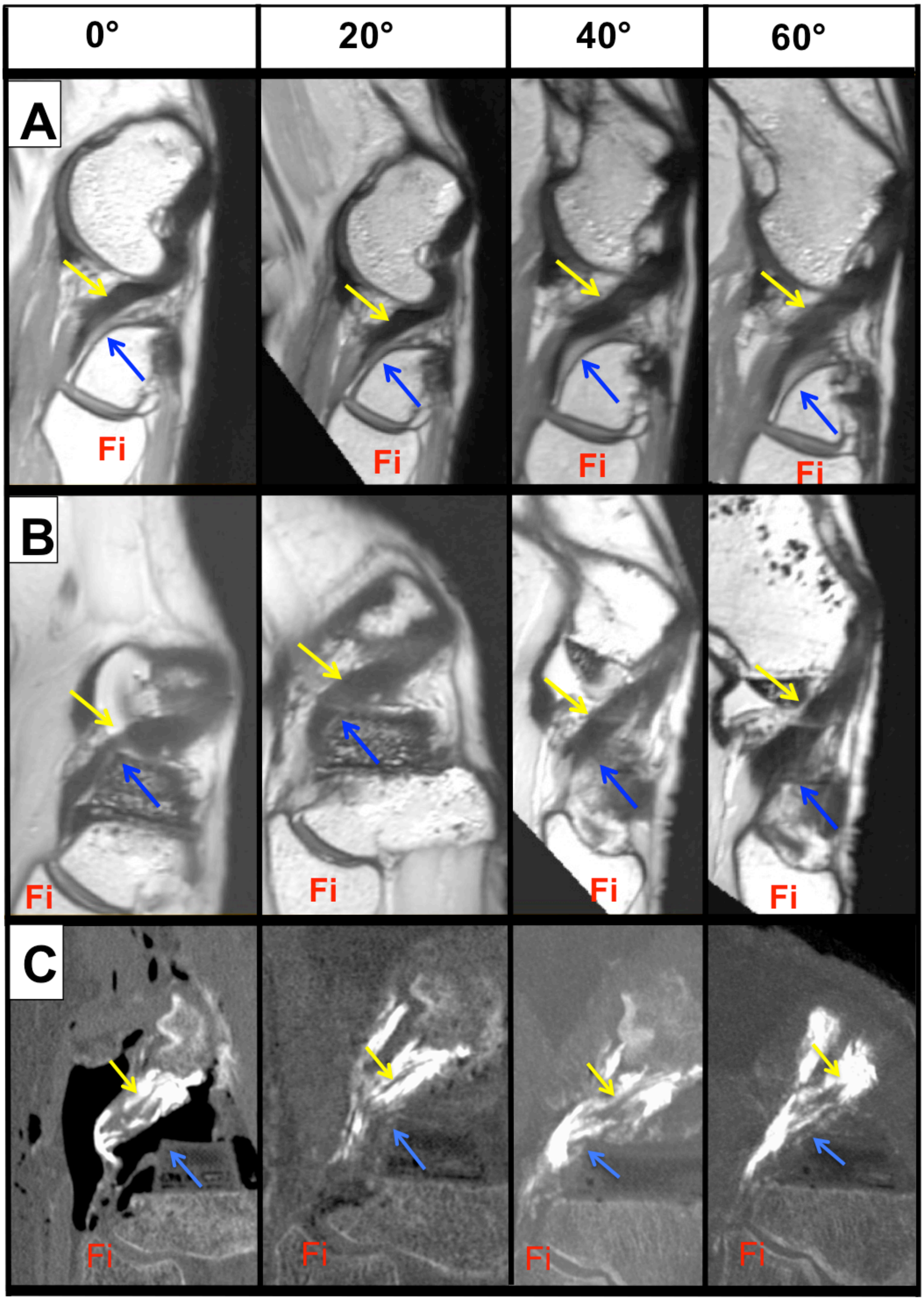

Figure 4: Visualization of the popliteus tendon (yellow arrow), the posterolateral corner of the lateral tibial plateau (blue arrow) and the head of the fibula (Fi) in an oblique parasagittal plane, during knee flexion. 4-A (MRI) In the preoperative knee, the popliteus has very intimate relations with the posterolateral corner of the lateral tibial plateau during the all range of motion . 4-B (MRI) Postoperatively, an impingement is visualized between popliteus and prosthetic plateau but the quality is poor 4-C (CT-scan fresh-frozen specimen). The popliteus tendon (yellow arrow) is visible as well as the tibial prosthetic plateau (blue arrow).

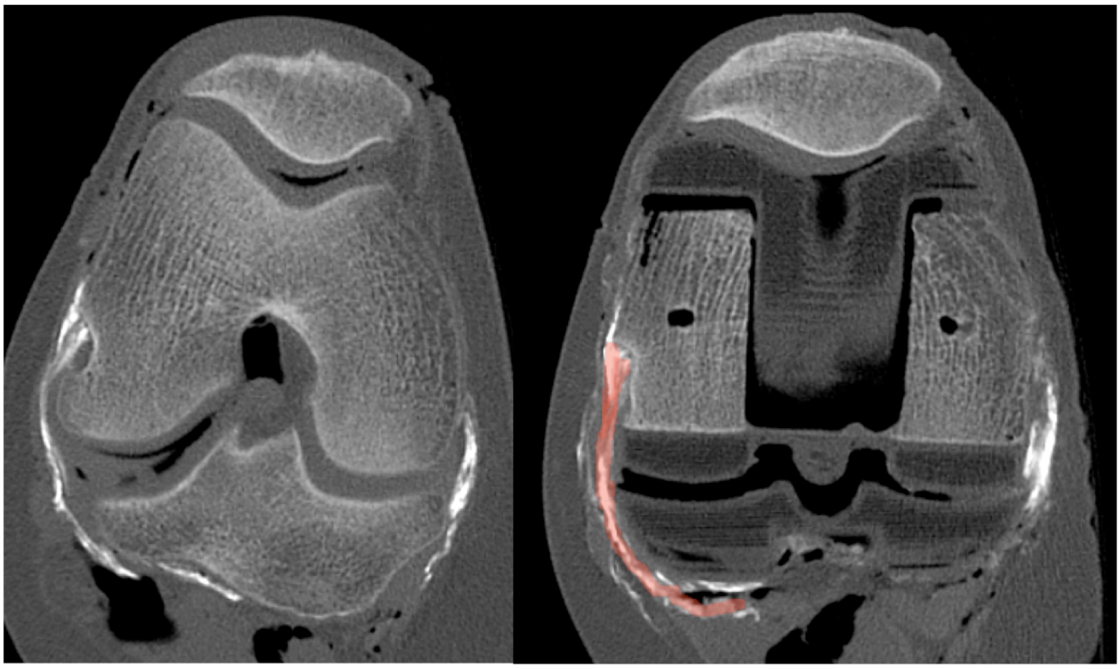

Figure 5: CT scan imaging of the popliteus tendon and MCL preoperatively (left) in a modified transverse plane. Postoperatively (right) the popliteus (red) and the MCL (white) are visible as well as their relationships with the bone and implant.

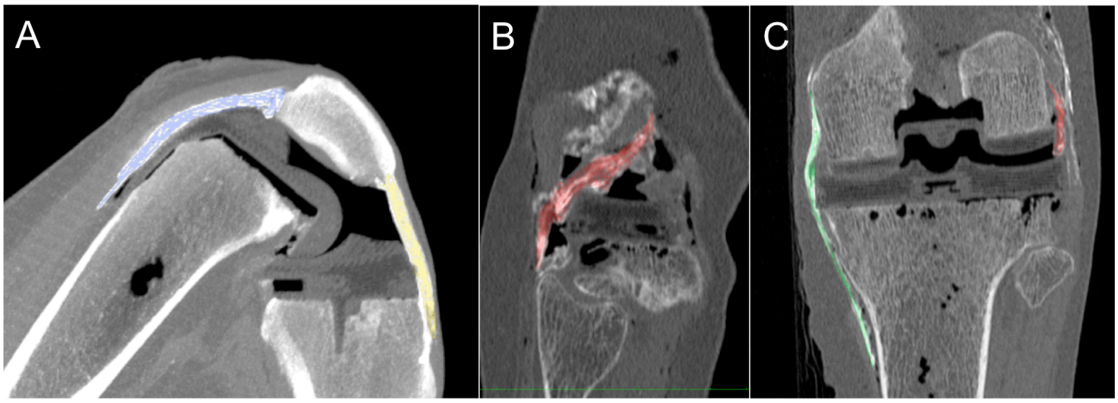

Figure 6: With CT scan on fresh specimen, the relationships between the implants and the soft tissues are visualized in the sagittal plane (quadriceps tendon in blue and patellar tendon in yellow) (A), in the oblique parasagittal plane (popliteus tendon in red) (B) and in the coronal plane (MCL in green and popliteus in red) (C).

4- *Range of motion*

Exploration from full extension to deep flexion appeared to be difficult with MRI. First, the small diameter of the MRI tube imposed a mid-shaft transection of the tibia and femur, which changed the quadriceps tension, creating a patella infera and induced a retraction of the hamstring muscles and the gastrocnemius. Second, beyond 90° a 'mirror image' appeared, which prevented full visualization of the knee. Third, MRI acquisition was time-consuming, requiring 30 minutes per sequence. The CT scans provided good quality images throughout the ROM (Figure 7).

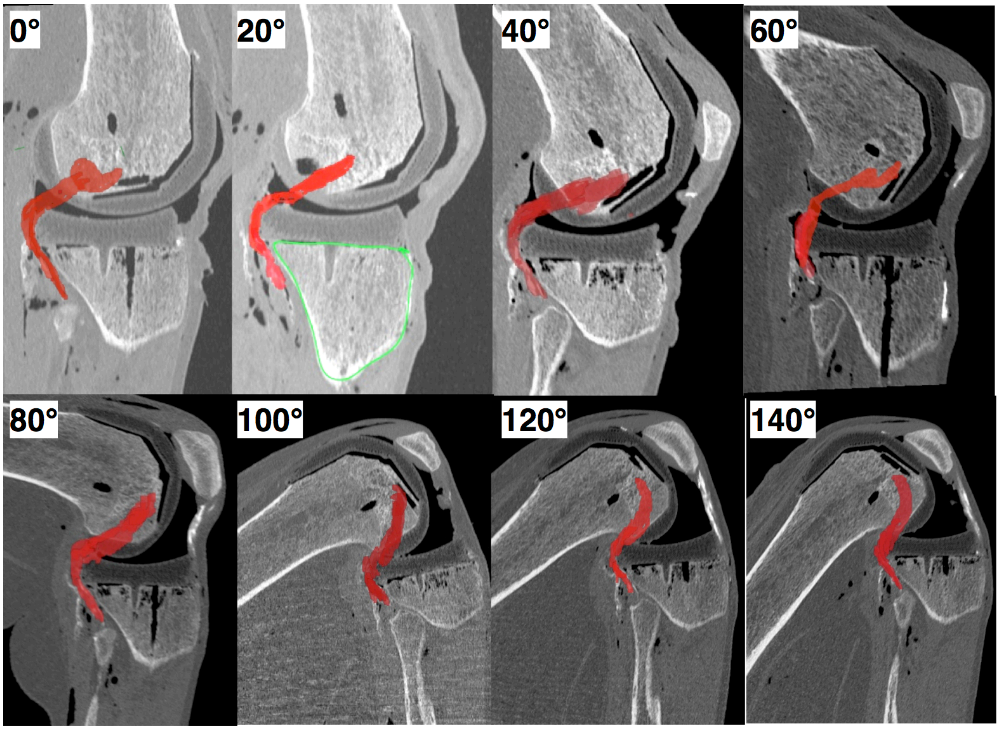

Figure 7: Sagittal view of the postoperative knee during the full range of flexion. The popliteus tendon is colored in red.

5- Three-dimensional reconstructions

3D reconstructions were done from group III, using CT scans on fresh-frozen specimens. Stereolithography (STL) files of the appropriate implant sizes were superimposed on the tibia and femur by manual matching, using the same landmarks. To compare the pre- and post-operative position of the soft tissues, the pre-operative Mimics® file was imported and matched with the post-operative file (Figure 8).

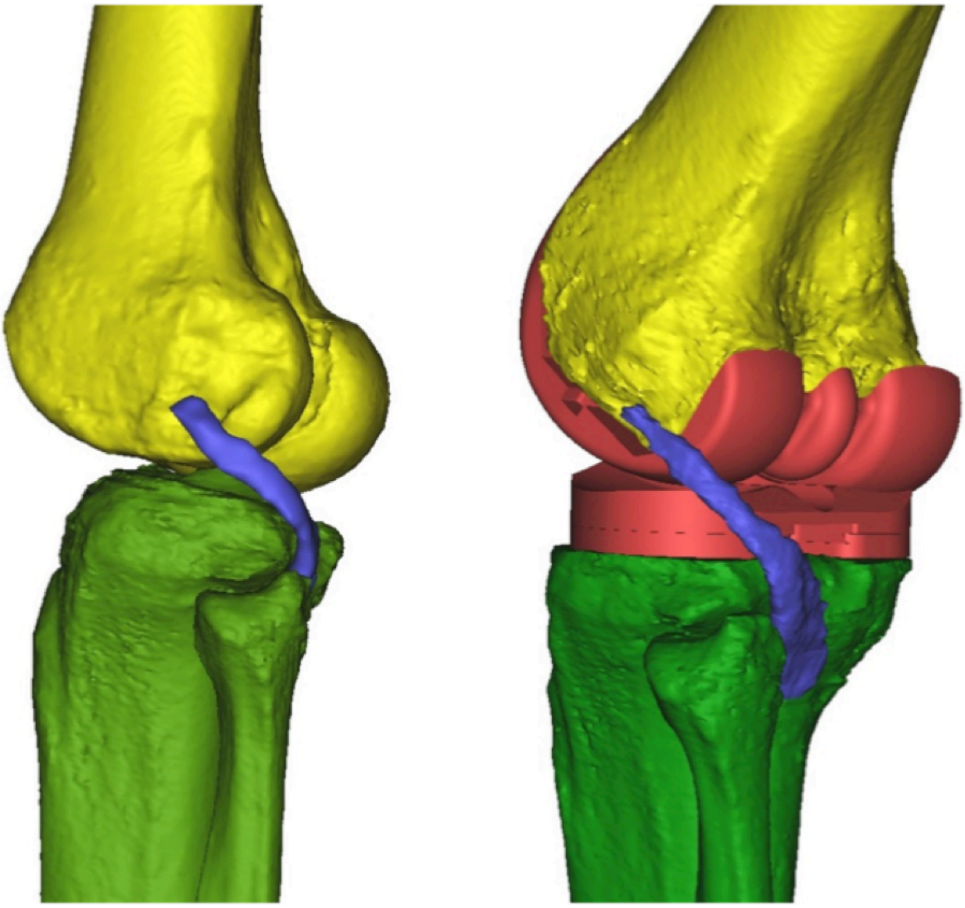

Figure 8: 3D reconstructions of the knee before (left) and after (right) implantation of the TKA. The modification of the position of the popliteus tendon is clearly visible.

Discussion

The role of soft tissue impingement in residual pain after joint prostheses has been emphasized only recently. In Total Hip Arthroplasty (THA) the first ilipsoas impingements were described in 1995 by Trousdale[23], and in TKA, painful impingements between the Popliteus Tendon and the lateral condyle were described by Barnes and Scott in 1995 and by Allardyce et al in 1997[1, 7]. Generally speaking, the influence of component overhang on residual pain after TKA has been investigated only in the last decade[5, 6, 8] and we can guess that the real rate of such impingements is underestimated due to the difficulties of clinical imaging. Better knowledge of interactions between soft tissues and implants would be critical to identify[2, 23] and prevent impingements by improving surgical techniques[2, 23] or implant design[3, 24].

To the authors' knowledge, the precise relations between TKA implants and surrounding soft tissues have never been investigated during the full ROM. Several computational models using finite element analysis have been developed, that contribute to this understanding[25, 26]. These models provide a platform for researchers to simulate knee flexion in weight-bearing conditions, with a given implant. They allow experimental testing using subtle changes from one test to another, i.e. slight variations of implant positioning, sizing or design. However these models have several limitations: (i) they are mostly designed to quantify muscle, ligament, and knee joint contact forces and areas; (ii) they rely only on data obtained from one or few specimens[25, 26]; (iii) a limited number of soft tissues is modeled, i.e. patellar tendon, rectus femoris and vastus intermedius[27] and (iv) their tracking during flexion-extension is only deduced from standard MRI in extension. Therefore, we intended to elaborate a protocol for soft tissue imaging around TKA, after implantation of commercially available prostheses, in realistic surgical conditions and on different human specimens. The goal was to provide images of the tracking of the soft tissues around the knee, before and after TKA, during the full range of flexion.

This work demonstrates that the use of implants made of acrylonitrile butadiene styrene and barium-free cement allows imaging of the implants without major scattering. While the study was originally intended to design and validate a method to image soft tissues around real metal and polyethylene implants, the authors were unable to overcome challenges caused by of image distortion and artifacts, despite repetitive involvement of engineers from the research and development department at the manufacturers of the scanners. The use of 3D printers provides the full range of sizes of many commercially-available prostheses and enables implantation in realistic conditions. The described CT technique should be used in the future to compare implants and to optimize their designs, with respect to interactions between implants and soft tissues. With the MRI protocol, neither the injection of embalming fluids nor the 20°C temperature of the room modified significantly the conductivity of the cadaveric tissues and their magnetic resonance properties. The two main reasons for which we do not recommend MRI are poor image quality of the implants and difficulties in differentiation between soft tissues and implants (Table 2). Also the presence of 'mirror images' in deep flexion, probably due to the small weight of the specimens, prevented to investigate deep flexion. With the CT scan technique, a good visualization of the injected soft tissues and their relationships with the implants was obtained during the full range of knee flexion.

Table 2: Advantages and disadvantages between MRI and CT-scan

	CT	MRI
Advantages	- Fast - Not expensive - Possible for full lower limb - Possible on fresh-frozen cadavers - Adequate visualisation of bone and soft tissues	- Visualisation of all the soft tissues
Disadvantages	- Needs injection of barium-sulfate - Impossible to inject all structures - Contrast medium does not reach the bony insertions	- Time consuming - Expensive - Needs transection of femur and tibia to flex the knee - Poor image quality for bone and implant - Require temperature monitoring

When choosing the size and/or design of components in TKA, one of the goals is to match the cortical contour of the bone cut area, avoiding overhangs[5, 6, 8, 28] but also optimizing the bone coverage[29], which may require some compromise[30]. Consequently, morphometric analysis, upon which implants are designed, are frequently based on measurements at the bone-cut levels done in vitro[31], in vivo[28, 32] or based on CT scans[33, 34]. However it has been recently demonstrated that patients with slightly undersized components had better outcomes than patients with normosized implants and that matching the bone-cut contours is an over-simplification[5]. We may assume that with several TKA implants, despite a good bone-implant fit at the resection planes, oversizing or 'over-stuffing' may occur in terms of volume.

The strength of the described CT scan protocol is that it provides precise 3D imaging of the soft tissues around TKA and may help to compare different implant designs, implant kinematics and also different joints. Its main limitation is that it required direct soft tissue injections via a lateral incision and an anteromedial arthrotomy, which can modify the normal anatomy. Another limitation is that it was not possible to quantify the clarity of soft tissues nor utility of each imaging technique, mainly because there was no existing 'gold standard', but also because routine clinical assessments of soft tissues are chiefly qualitative or semi-quantitative. Finally, the images were acquired for this study without weight-bearing or natural muscle tensions, which can be simulated in finite element models. Nevetheless, by virtue of conformity of articular surfaces in TKA, we can assume that soft tissue contacts with bone and implant surfaces are similar in a weight-bearing situation.

Conclusion

The experimental approach described in this study was successful in visualizing the real relationships between the soft tissues and the implants before and after TKA and throughout the range of motion. The coordinate system allows to localize precisely the different anatomic structures and to quantify changes due to prosthetic implantation. This protocol permits accurate analysis of soft tissue displacements following implantation of TKAs of different designs, sizes and alignments. A perspective could be to match the anatomic data obtained from this work with computational models.

Competing interests

No financial support was received for this investigation.

One or more authors received royalties from: Tornier, DePuy-Synthes, and Smith& Nephew.

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11. Popliteus impingement after TKA may occur with well-sized prosthesis

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Abstract

Purpose: To determine the mechanisms and extents of popliteus impingements before and after TKA and to investigate the influence of implant sizing. The hypotheses were that (i) popliteus impingements after TKA may occur at both the tibia and the femur and (ii) even with an apparently well-sized prosthesis, popliteal tracking during knee flexion is modified compared to the preoperative situation.

Methods: The location of the popliteus in three cadaver knees was measured using computed tomography (CT), before and after implantation of plastic TKA replicas, by injecting the tendon with radiopaque liquid. The pre- and post-operative positions of the popliteus were compared from full extension to deep flexion using normosized, oversized and undersized implants (one size increments).

Results: At the tibia, TKA caused the popliteus to translate posteriorly, mostly in full extension: 4.1±2 mm for normosized implants, and 15.8±3 mm with oversized implants, but no translations were observed when using undersized implants. At the femur, TKA caused the popliteus to translate laterally at deeper flexion angles, peaking between 80º – 120º: 2±0.4mm for normosized implants and 2.6±0.5 mm with oversized implants. Three-dimensional analysis revealed prosthetic overhang at the postero-superior corner of normosized and oversized femoral components (respectively, up to 2.9mm and 6.6mm).

Conclusions: A well-sized tibial component modifies popliteal tracking, while an undersized tibial component maintains more physiologic patterns. Oversizing shifts the popliteus considerably throughout the full arc of motion. This study suggests that both femoro- and tibio-popliteus impingements could play a role in residual pain and stiffness after TKA.

Introduction

Residual pain and poor outcomes after Total Knee Arthroplasty (TKA) can be attributed to soft tissues impingements, which could arise due to prosthetic overhang at the femur[1, 2] or the tibia[3]. Impingements may involve various anatomic structures such as the medial collateral ligament (MCL), the iliotibial band, the popliteus tendon, the patellar tendon and the medial and lateral patellar retinaculum[1, 2, 4, 5]. The popliteus tendon is of special interest due to its intra-articular location and its close contact with the posterolateral tibial plateau and the lateral condylar margin[6].

In a normal knee, the popliteus remains in close contact with the convex posterolateral area of the lateral tibial plateau, up to the popliteus hiatus, where it is stabilized by the popliteomeniscal fascicles[6-11]. It then crosses the margin of the lateral condyle and inserts anterior and distal to the lateral epicondyle[12-15]. In full extension, the popliteus is engaged in a distal indentation of the lateral condyle, called the Sulcus Statorius[11]. During flexion, it glides over the bumpy margin of the lateral condyle, and beyond 100° of flexion, it lies entirely within the groove of the Sulcus Popliteus (Figure 1)[15, 16].

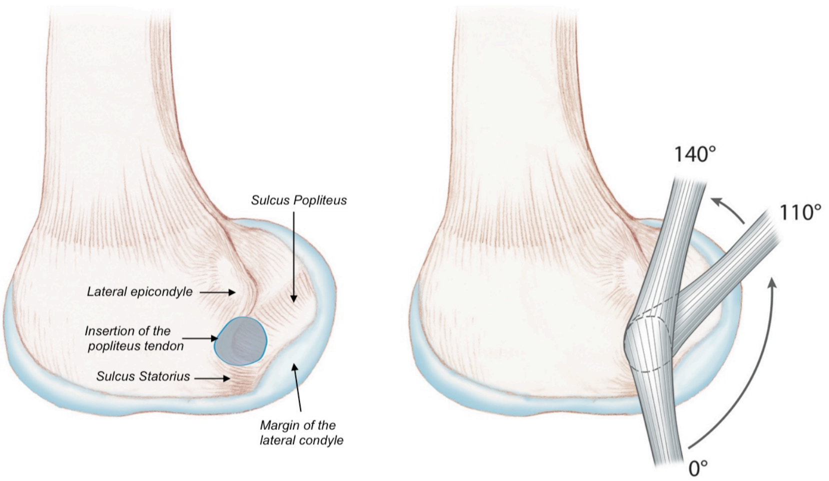

Figure 1: In native knees, the popliteus tendon inserts in an area located distal to the lateral epicondyle. In extension, the tendon is seated in the sulcus statorius. During flexion it glides along the margin of the lateral condyle and then seats in the popliteus sulcus beyond 100° of flexion.

In a TKA, the thickness of the tibial component is selected to restore the joint line and to match the contours of the resected surfaces[17-20]. Therefore, a superstructure of polyethylene is generally built above the posterolateral area of the tibial plateau, leading to a potential risk of popliteus impingement (Figure 2). At the femur, any shape difference between the prosthetic and the native lateral condylar margin, such as induced by the design, the sizing or the positioning of the femoral component, potentially affects the tracking of the popliteus[21, 22]. Indeed, impingements have been reported secondary to friction against femoral osteophytes or overhanging prosthetic condyles[21, 23, 24] and have been successfully treated by arthroscopic popliteus release[23].

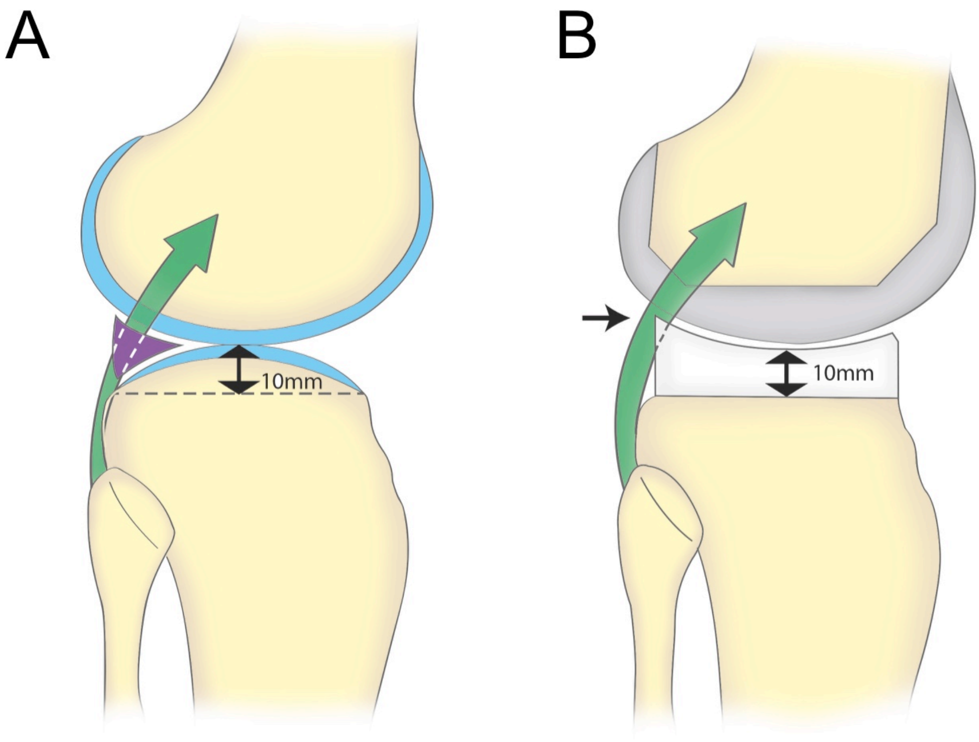

Figure 2: In a normal knee (A) the lateral tibial plateau is convex in the sagittal plane. The popliteus (green) is in contact with the posterolateral margin of the plateau and passes through the popliteus hiatus within the meniscus (purple). The tibial resection in TKA (dashed line) is typically performed 10mm below the convexity of the plateau. After TKA (B) the PE insert does not reproduce the convex shape of the native plateau and impingement occurs at the postero-superior border of the base-plate.

It has been demonstrated that mediolateral overhang of the femoral component could cause residual pain after TKA, and that slightly under-sizing the femoral component may improve pain scores[1, 2]. However, under-sizing may lead to implant subsidence or tibiofemoral instability[25] and could compromise bone-implant fit[26]. Many recent femoral components are available in 'standard' or 'narrow' versions, and allow greater tibia-femur size mismatch that enable surgeons to fine-tune mediolateral sizing. Nevertheless, the optimal sizing, exact-fit or slight under-coverage, remains controversial.

The purpose of this study was to determine the mechanisms and extents of popliteus impingements by examining the bony and prosthetic contours of knees before and after TKA and to investigate the influence of implant sizing. The study hypotheses were that (i) popliteus impingements after TKA may occur at both the tibia and the femur and (ii) even with an apparently well-sized prosthesis, the position or tracking of the popliteus during knee flexion is modified compared to the preoperative situation.

Material and Methods

The location of the popliteus tendon was studied on three fresh frozen cadaver knees throughout the flexion-extension range, using computed tomography (CT), before and after implantation of TKA. The cadavers had been donated for research by testament and our institutional review board granted ethical approval for this study in advance (Reference number EC-2014/0847). None of the cadaver knees had history of previous surgery.

Specimen preparation

With a lateral longitudinal approach, the ilio-tibial band was incised and the popliteus tendon was dissected from the condyle to the musculo-tendinous junction. A mixture of glycerol

(60%) and bariumsulfate (40%) was injected in the popliteus from its insertion to render the entire tendon radio-opaque and enable its visualization in isolation from surrounding soft tissues. This technique was described for imaging of the posterior cruciate ligament[27].

The three knees were then scanned using a 64-slice multidetector CT scanner (Siemens Sensation, Munich, Germany) with the lower limb in supine position and included the femoral head and the ankle to calculate the mechanical tibiofemoral angle (TFA). The knees were then scanned using 0.6mm thick slices from full extension to full flexion in 20° increments.

TKA implantation

The TKA implants used were plastic replicas of the fixed-bearing postero-stabilized HLS KneeTech® (Tornier SA, Montbonnot, France). The specimens were produced by the manufacturer using rapid prototyping: Fused Deposition Modeling FDM® with a Stratasys Dimension Elite™ machine (Eden Prairie, MN, USA) from a non radio-opaque and non-magnetic polymer (Acrylonitrile butadiene styrene). Implantation was performed through a medial parapatellar approach using the conventional instrumentation for a tibia first technique with orthogonal cuts and a posterior referencing technique for the resection of the posterior condyles. The femoral component was aligned with the surgical transepicondylar axis (TEA), and the tibial component was aligned with the center of the Anterior Tibial Tuberosity. Implants were cemented with barium-free polyester (Polyester Demaere, Brussels, Belgium).

Specimen #1 was implanted with a 'normosized' TKA, where the contour of the tibial component fits almost exactly with the tibial cortex and where the femoral components did not overhang the bony contours in any visible area of the bone cuts. Specimen #2 was implanted with an 'undersized' TKA (one size smaller), with the contour of the tibial base-plate about 3mm inside the tibial cortex and with a 3mm border of non-covered resected bone at the posterior portion of the distal femoral cut. Specimen #3 was implanted with an ‘oversized’ FB-TKA (one size larger), with the tibial implant overhanging the bony contour of the lateral tibial plateau by about 3mm and the femoral component overhanging of about 3mm at the anterodistal area (anterior chamfer).

CT scan analysis

Postoperatively, the full lower limb was scanned following the same imaging protocol used for the preoperative scans, to verify that the final alignment was in the range 180°±3°. Raw DICOM images enabled visualization of the popliteus during flexion before and after TKA implantation (Figure 3). From these raw DICOM images, the popliteus was digitized by manual segmentation at each slice level, using Mimics® software (Materialize®, Leuven, Belgium) in order to generate three-dimensional (3D) reconstructions. Stereolithography files (STL) of the implants obtained from the manufacturer were superposed with the raw DICOM images (Figure 4). Coordinates of digitized points were exported to spreadsheets and processed using Matlab® (MathWorks®, Natick, MA, USA).

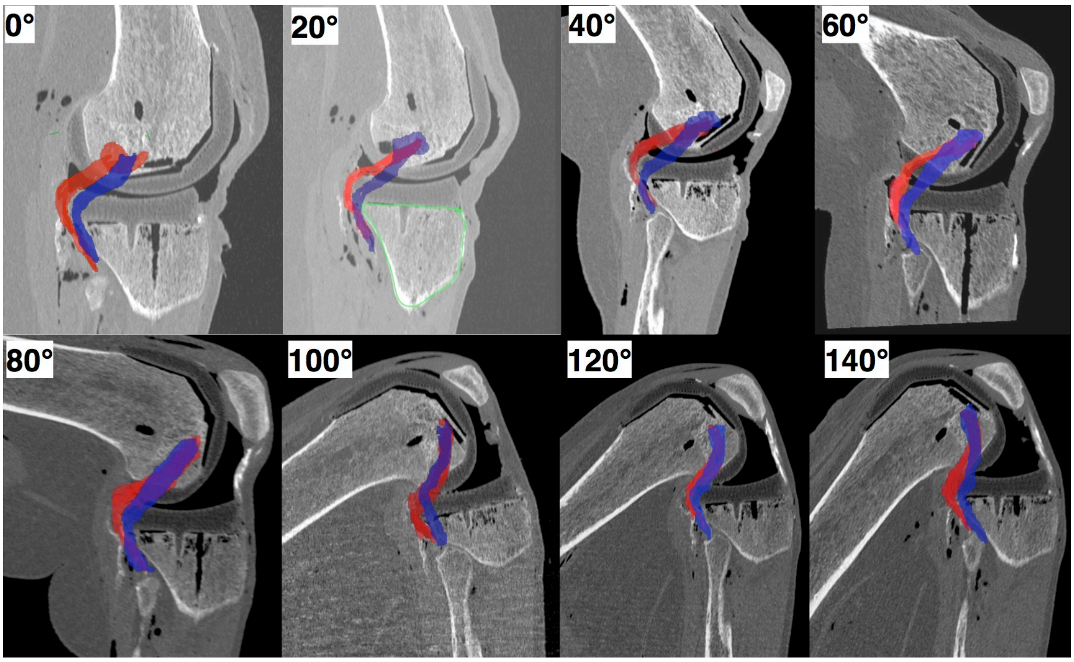

Figure 3: Imaging of the Popliteus Tendon from raw DICOM images, in a native (preoperative, blue) knee and in an implanted (postoperative, red) knee with an oversized component.

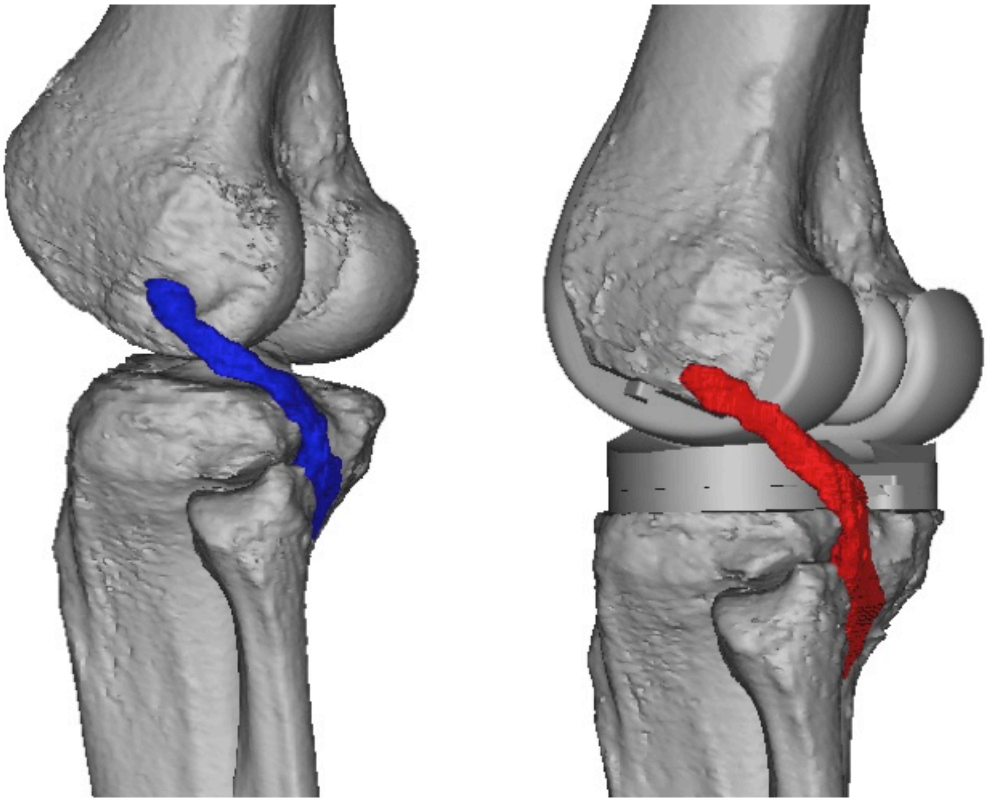

Figure 4: Three-dimensional reconstruction of the knee, before and after implantation of a 'normosized' TKA. The popliteus crosses the posterolateral aspect of the tibial plateau. Bone reconstructions were obtained using Mimics® software (Materialize®) and implant models (STL files) were superposed.

Tibial coordinate system

The tibial coordinate system was established with its origin at the center of the tibial keel at the level of the tibial cut, which defined the transverse plane. The anteroposterior axis intersects the origin, perpendicular to the posterior tibial margin; the mediolateral axis was parallel to the posterior tibial margin intersecting the origin, and the proximodistal axis was perpendicular to the transverse plane intersecting the origin.

The overlap of the popliteus on the native tibial plateau was measured at the level of the tibial cut after superimposing the popliteus, as seen on each CT slice. The 'maximum overlap distance' (MOD) was measured between the cortical contour of the plateau and the inner point of the popliteus in three distinct zones (Figure 5).

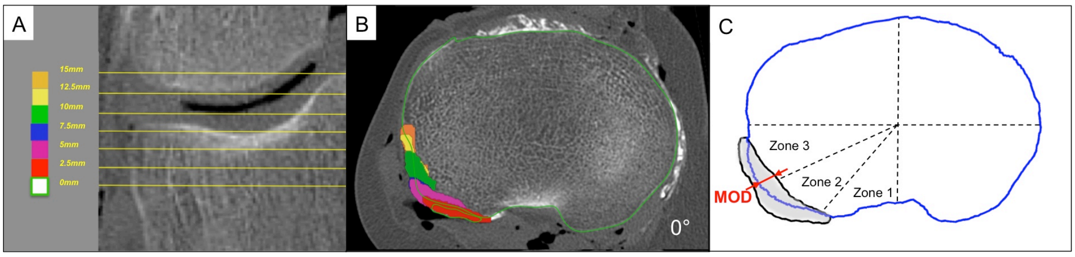

Figure 5: CT scan of the knee at 0° of flexion: (A) coronal view indicating different slices analyzed (0mm corresponds to the tibial resection level; 10 mm corresponds to the joint line,); (B) transverse view at the level of tibial resection illustrating the position of the popliteus at different levels above; (C) representation of the entire transverse area covered by the popliteus (grey) obtained using Matlab®. The maximum overlap distance (MOD, red arrow) was measured separately in three sectors of the posterolateral quadrant: Zone 1 (0° to 30°), Zone 2 (30° to 60°) and Zone 3 (60° to 90°).

The pre- and post-operative positions of the popliteus were analyzed and compared on each slice in the transverse plane, from full extension (0º) to full flexion (140º). The geometric center of the popliteus was used to determine the anteroposterior distance (APD) and mediolateral distance (MLD) with respect to the origin (Figure 6). The pre-post operative translations of the popliteus were measured in the entire area of the prosthetic plateau (cf. additional material), with a special focus at 0mm (tibial cut), 5mm (middle of the prosthetic tibial plateau) and 10mm (superior border of the plateau).

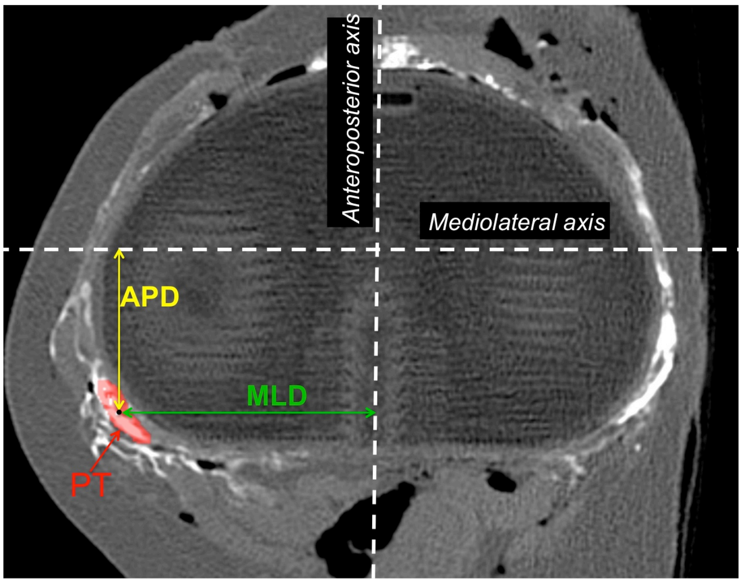

Figure 6: The anteroposterior distance (APD) and mediolateral distance (MLD) were measured in the transverse plane from the origin of the tibial coordinate system orthogonally to the geometric center of the popliteus (red).

Femoral coordinate system

The femoral coordinate system (Figure 7) was established with the mediolateral axis being the line that intersects the centers of the circles that best fit the femoral condyles. The origin was defined as the midpoint between the medial and lateral femoral cortices along the mediolateral axis. The proximodistal axis was set parallel to the popliteus tendon, between its femoral insertion and the point where it crosses the lateral condylar margin. The frontal and transverse planes, perpendicular respectively to the anteroposterior and proximodistal axes, remained unchanged relative to the popliteus during knee flexion (static) but moved relative to the femur during flexion (dynamic). Only the sagittal plane remained unchanged relative to both the femur and the popliteus throughout flexion.

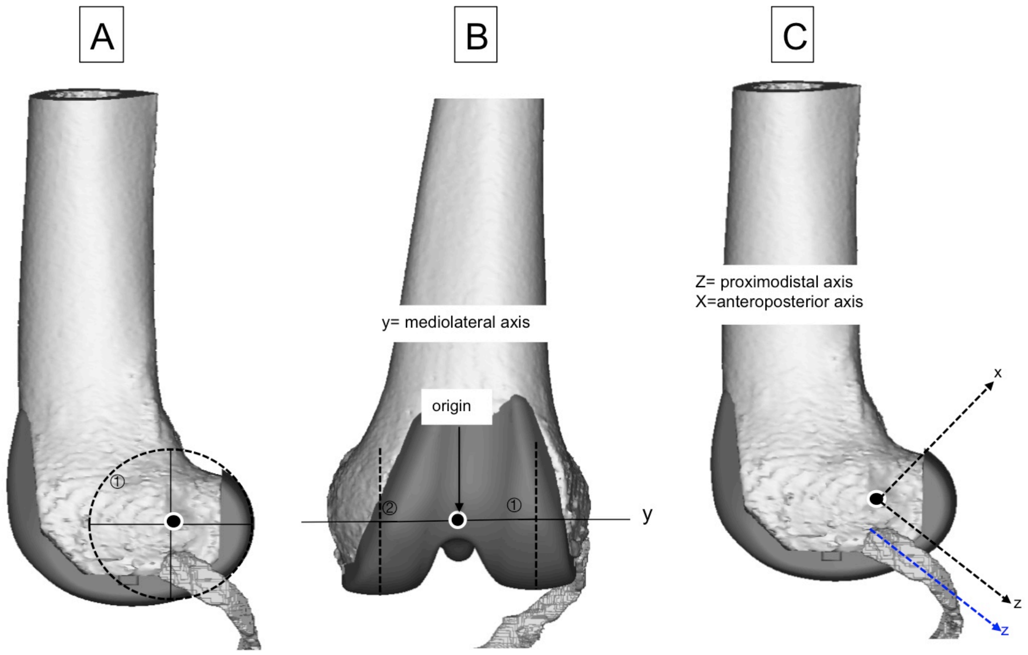

Figure 7: The femoral coordinate system was established with the mediolateral axis as the line that intersects the centers of the circles that best fit the femoral condyles (A). The origin was defined as the midpoint between the medial and lateral femoral cortices along the mediolateral axis (B). The proximodistal axis was set parallel to the popliteus tendon, between its femoral insertion and the point where it crosses the lateral condylar margin and the anteroposterior axis was perpendicular to the popliteus tendon at its femoral insertion (C).

The pre- and post-operative mediolateral positions of the popliteus were measured in the transverse plane, as distances from the sagittal plane to the geometric center of the popliteus. Measurements were repeated at all flexion angles, from the femoral insertion of the popliteus to the joint line, with a special interest in the area where the popliteus crosses the condylar margin. The maximum mediolateral distance (MLD-max) was measured at the apex of the lateral condylar margin, where the risk of prosthetic impingement is greatest (Figure 8).

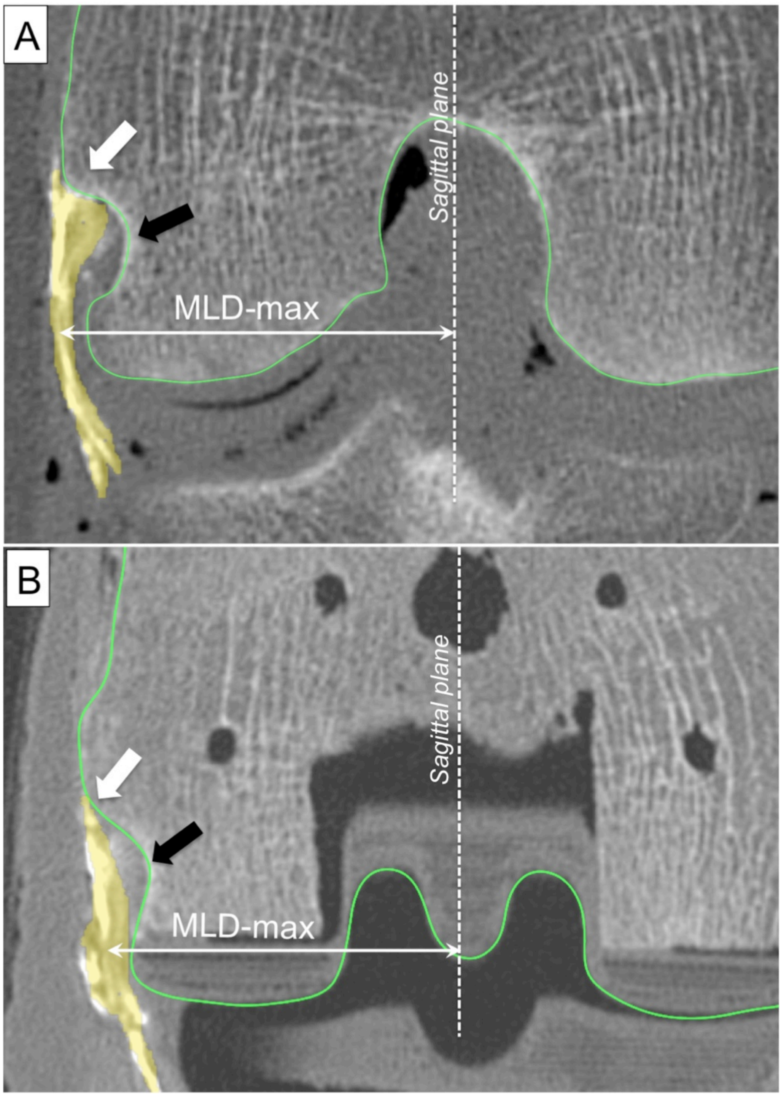

Figure 8: Measurements before (A) and after (B) TKA implantation. The popliteus is colored in yellow and the bony or prosthetic contours are outlined in green. The white arrow indicates the femoral insertion of the popliteus, and the black arrow points to the popliteus sulcus. The maximum mediolateral distance (MLD-max) was measured at the apex of the lateral condylar margin.

Statistical analysis

Inter- and intra-observer repeatability were determined using 40 measurements performed by three different observers. For inter- and intra-observer testing, the interclass correlation coefficients were respectively r=0.82 and r=0.83. Statistical analyses were conducted using SPSS software (IBM, Armonk, NY, USA).

Results

Tibia-popliteus relationships

In native knees (Figure 9, Table 1), the popliteus overlapped the posterolateral aspect of the tibial plateau in Zones 2 and 3, between full extension and 40° of flexion. No overlap was observed in Zone 1 throughout the flexion range. The maximum overlap distance (MOD) was 4.8mm observed in Zone 3, but some inter-specimen variability was observed.

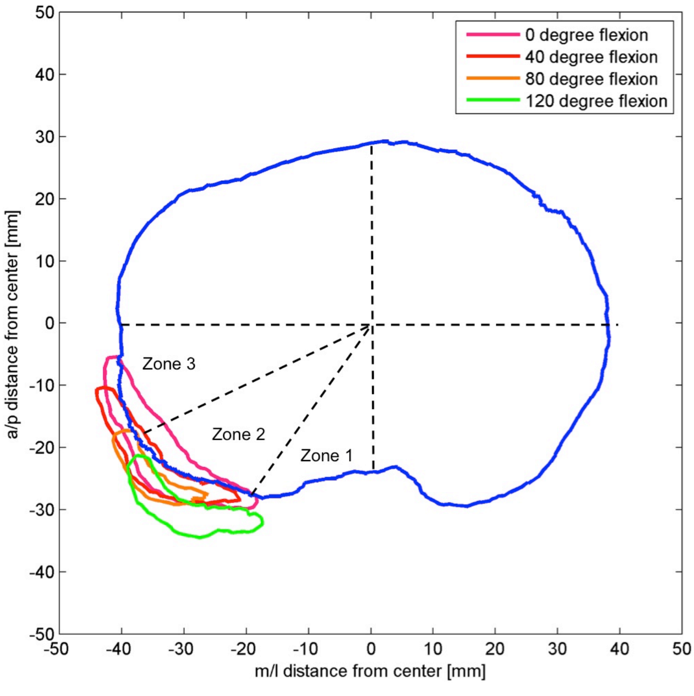

Figure 9: Projection of the popliteus on the tibial plateau at the resection level throughout the range of flexion in the native knee. In extension (pink), the tendon overlaps the contour of the tibial plateau considerably, whereas at 40° flexion (red) the overlap is minimal. At 80° flexion (orange) and 120° flexion (green) the popliteus never overlaps the tibial plateau.

Table 1: Maximum overlap distance (mm)

Flexion angle	Zone 2			Zone 3		
	Mean ± SD	Max	Median	Mean ± SD	Max	Median
0˚	1.2 ± 1.9	4.1	0.3	1.4 ± 2.3	4.8	0.4
20˚	1.3 ± 1.1	2.4	1.3	1.1 ± 1.0	2.5	0.7
40˚	0.5 ± 0.6	1.0	0.5	0.4 ± 0.6	1.3	0.2
60˚	0.2 ± 0.4	0.9	0.0	0.0 ± 0.6	0.1	0.0
80˚	0.0 ± 0.0	0.0	0.0	0.1 ± 0.1	0.2	0.1
100˚	0.1 ± 0.3	0.5	0.0	0.0 ± 0.0	0.0	0.0
120˚	0.3 ± 0.5	1.0	0.0	0.0 ± 0.0	0.0	0.0
140˚	0.0 ± 0.0	0.0	0.0	0.0 ± 0.0	0.0	0.0

After implantation of a normosized TKA (Figure 10 and 11), the popliteus was posteriorly translated, from full extension to 100° of flexion, but an anterior translation was observed thereafter in deep flexion. The greatest deviations were observed at the superior tibial border, 10mm proximal to the tibial cut. The mean posterior translation of the popliteus at the plateau level was 4.1±2mm (range; 1.7 to 7.7) in full extension, and 3.5±2.2mm (range; 0.7 to 7) at 20° of knee flexion. A medial translation of the popliteus was also observed between 0° and 100° of flexion, with a maximum of 3.1mm at 20° of flexion and a lateral translation was observed in deep flexion with a maximum of 3mm at 140° flexion. When an oversized TKA was implanted, a greater posterior translation was observed throughout the range of movement, at all levels of the prosthetic tibial plateau. The mean posterior translation of the popliteus was 15.8±3mm (range; 9.8 to 19.5) in full extension and 4.3±0.8 mm (range; 2.9 to 5.3) in deep flexion. The tendon appeared also to be laterally translated throughout the range of flexion. When an undersized TKA was implanted, the popliteus was anteriorly translated during the entire range of flexion and a medial translation less than 2.5 mm was also observed.

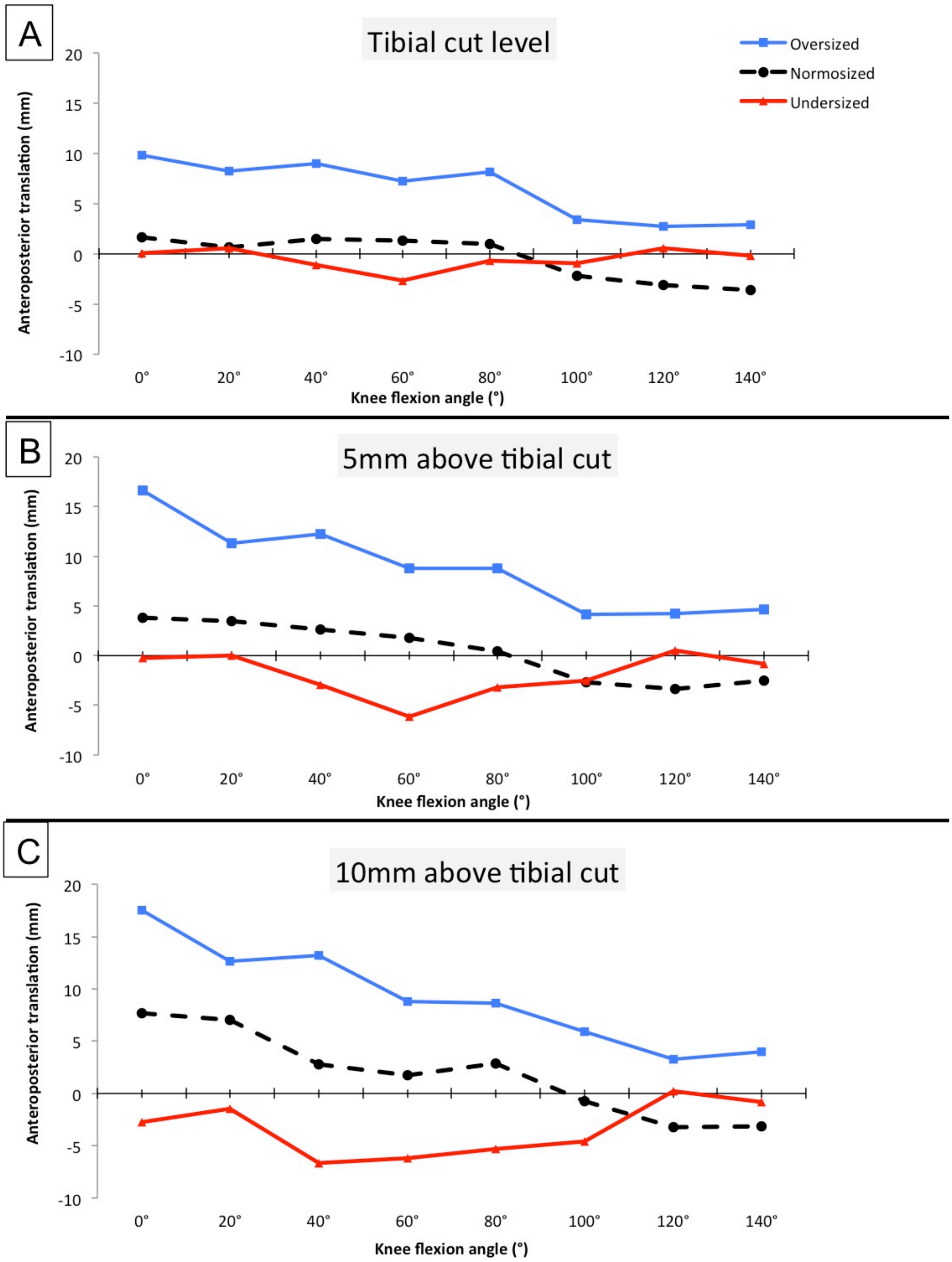

Figure 10: Posterior translation of the popliteus after TKA compared to its native position (vertical axis) throughout the range of knee flexion at: (A) the tibial cut level, (B) 5 mm above the tibial cut, and (C) 10mm above the tibial cut.

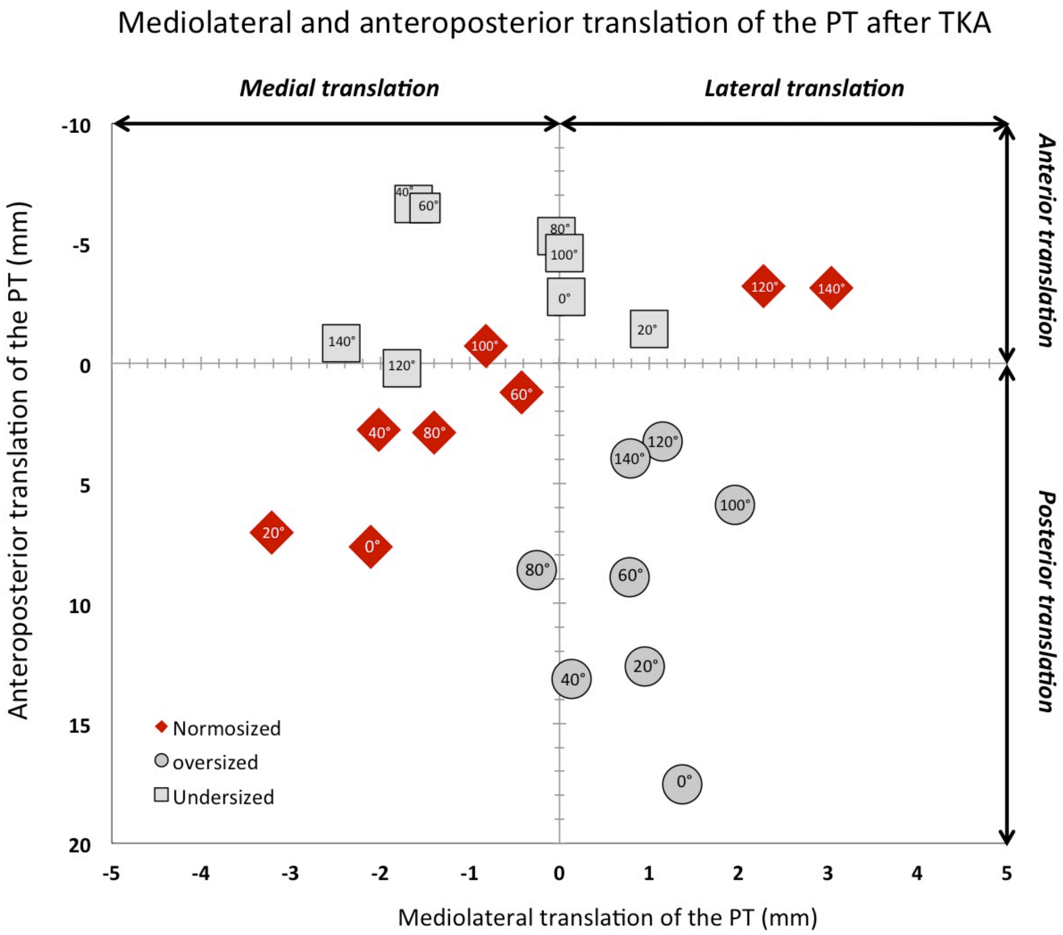

Figure 11: Graphic representation of anteroposterior and mediolateral translations of the popliteus at different flexion angles and for different implant sizes. In oversized TKA the popliteus is displaced posteriorly and laterally whereas in undersized TKA it is displaced medially and anteriorly.

Femur-popliteus relationships

In native knees, the mediolateral position of the popliteus followed the bony contour of the lateral condyle. Between 0° and 40° of flexion, the popliteus disengaged from the sulcus statorius and translated slightly laterally and then medially by 3.5±0.4mm (range; 2.9 to 3.9) between 40° and 120° of flexion, until it was fully seated into the popliteus sulcus.

With a normosized TKA (Figure 12), compared to the preoperative situation, the popliteus was more medial between full extension and 60° of flexion, beyond which it was lateralized until deep flexion. With an oversized TKA, the same pattern was observed with further lateralization compared to the normosized TKA. The maximum lateralization was observed at 80° of flexion, which then decreased progressively at greater flexion angles. With an undersized TKA, the popliteus was medialized from full extension to 120° of flexion compared to the preoperative knee. Three-dimensional analysis revealed prosthetic overhang at the postero-superior corner normosized and oversized femoral components (respectively, up to 2.9mm and 6.6mm), which could explain the 'paradoxical-lateralization' of the popliteus during flexion (cf. Figure A2 in additional material).

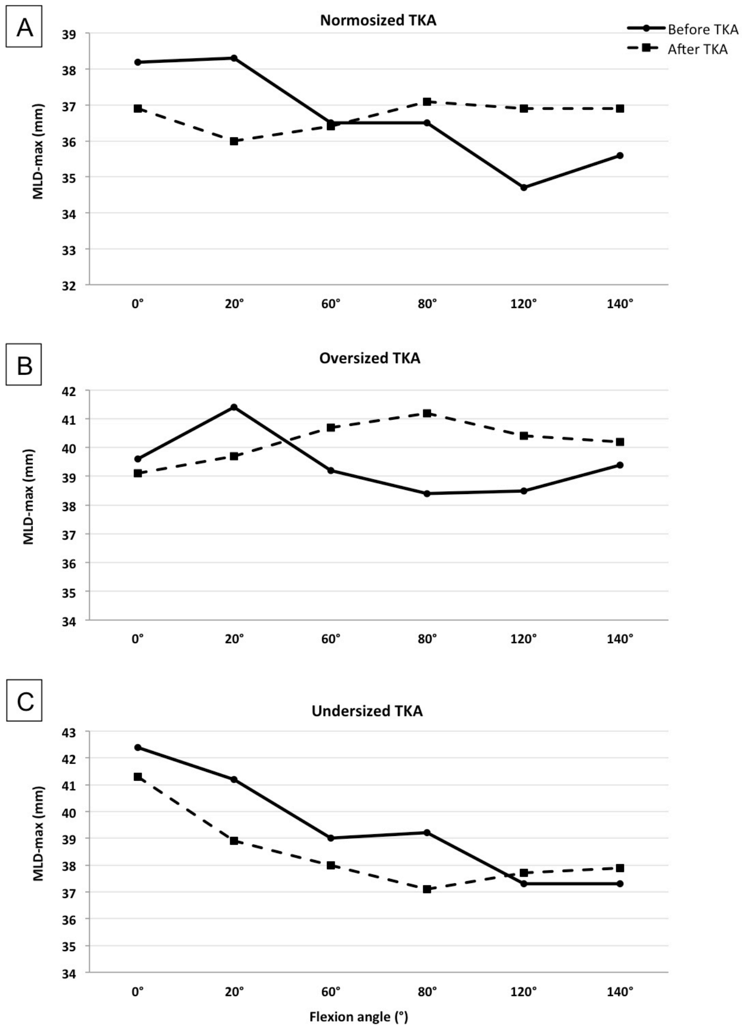

Figure 12: The maximum distance (MLD-max) between the sagittal plane and the geometric center of the popliteus before (solid) and after (dashed) TKA implantation with normosized (A), oversized (B) and undersized (C) prosthesis.

Discussion

The main finding of this study is that a well-sized tibial component modifies popliteal tracking, while an undersized tibial component maintains more physiologic patterns. The data also demonstrate that oversizing the tibial component by one size increment shifts the popliteus considerably throughout the full arc of motion. These results confirm previous clinical investigations that reported better pain scores in patients with ‘undersized’ implants[1], and poorer outcomes in patients with posterior tibial overhang[3]. Why an ‘anterior translation’ of the popliteus was observed in deep flexion with a normosized prosthesis remains unclear. An explanation could be that sacrificing the popliteo-meniscal fascicles during implantation, secondary to lateral meniscectomy, destabilizes the tendon in deep flexion[9, 10].

Another finding was that the popliteus-condyle contact is modified after TKA throughout the flexion range, whatever the sizing option, which resulted in a ‘reversed pattern’. From full extension to mid-flexion, the popliteus was medialized because the margin of the prosthetic lateral condyle does not reproduce the smooth ridge of the native lateral condyle, which is often removed during surgery. From mid to deep flexion, the tendon was lateralized due to prosthetic overhang at the lateral condyle.

This study had some limitations: First, even if this study was based on pre-post operative comparison, the limited sample size remains a limitation of this study and anatomic variations may modify the bone-popliteus or implant-popliteus relationships that we observed. Second only one implant design was used and it is unclear whether our conclusions can be extended to other implants. It would be valuable to do this investigation with other designs such as medial-pivot or asymmetric TKAs. The posterior translation of the tendon may also be influenced by prosthetic kinematics and it could be useful to compare postero-stabilized, cruciate-retaining and deep-dished TKAs. Third, this was a non weight-bearing investigation, which could limit our conclusions, though by virtue of conformity of articular surfaces in postero-stabilized TKA, it can be assumed that the contact of the popliteus with bone and implant surfaces are similar in weight-bearing[28-30]. Fourth, it is a cadaveric work, and even with fresh specimens, one may argue that the behavior of the soft tissues was altered. Fifth, the use of CT scans required injecting the popliteus via a lateral incision, which can modify its elasticity. In a preliminary investigation, the authors tested MRI, which proved inaccurate due to technical problems such as mirror images in deep flexion, poor quality images due to temperature variations within specimens, small diameter of the MRI tube, which does not accommodate the knee in flexion. Finally, the study did not analyze the strain in the popliteus because inserting strain gauges[31] would compromise the image quality by scattering and even the use of chromium-steel spheres precludes good soft tissue analysis[32].

Residual pain is a very frustrating situation after TKA and identifying the cause can be challenging[33]. Soft-tissue impingements have been described as an etiology but mostly in patients with overhanging components[1-3] and little is known about the behavior of the soft tissues surrounding a well-sized TKA. There is little published literature on the diagnosis and treatment of popliteus impingement after TKA. While some authors reported successful pain relief after tendon release[21, 23, 24], none investigated the pathophysiology in detail. Allardyce et al.[23] reported results of arthroscopic release in two patients presenting ‘popliteus tendon dysfunction’ but did not describe the nature and location of the impingement. Likewise, Kazakin et al.[24] observed snapping popliteus tendon during TKA. The consequences of such popliteus tendon release in prosthetic knees are unclear. While De Simone et al.[34] reported lower function score, neither Kesman et al.[35] nor Ghosh et al.[36] observed adverse effects after popliteus transection, *in-vivo* or *in-vitro*. Recently, Cottino et al.[37] reported an increased TKA laxity after popliteus section, both with cruciate-retaining and postero-stabilized prosthesis.

It is worth specifying that our detailed measurements, made on cadaver knees using contrast agents, would be impossible to replicate in vivo due to the challenge of imaging soft-tissues around cobalt-chromium implants. The difficulty of diagnosing popliteus impingements could hence account for the paucity of literature on the subject and the incidence of residual pain after TKA that remains unexplained.

To avoid popliteus impingements after TKA, slightly undersizing the tibial component could be an option, in order to preserve a peripheral bony margin at its posterolateral corner. It must be noted, however, that excessive under-sizing could lead to implant subsidence and failure[25]. The use of anatomic base-plates, which replicate the tibial asymmetry may help the surgeon to both undersize laterally and preserve a good medial coverage. With symmetric base-plates, posterior overhang was observed at the lateral plateau in 87% of patients[3],while both Dai et al.[17] and Martin et al.[19] recently demonstrated that asymmetric tibial base-plates provide better conformity to resected surfaces. Theoretically an ideal TKA should closely reproduce the shape of the resected articular surfaces, but this is difficult to achieve at the tibia because the polyethylene must respect a degree of congruency with the prosthetic condyles[38-40] and the lateral compartment presents high geometric variability[5, 38, 41, 42]. Consequently, none of the current TKA designs reproduce the convex shape of the posterolateral tibial plateau, though some lateral UKA models feature 'dome-shaped' tibial base-plates with bi-concave polytheylene inserts, to better reproduce natural anatomy and kinematics[43, 44].

This study reports that a posterolateral condyle overhang may occur even with normosized implants. The reality of this phenomenon may be criticized as it has been infrequently reported in the literature. Hirakawa et al.[45] in a series of 40 TKAs in a Japanese population reported a overhang of the posterolateral condyle greater than 3mm in 25 patients and suggested to reduce the dimensions of the posterolateral condyle in TKA. Shah et al.[46] in an Indian population also reported overhang of the posterolateral condyle when implanting a standard TKA. Mahoney et al.[2] measured intraoperatively overhang with the Scorpio prosthesis in several zones of the femur but did not detail the incidence of posterior condyle overhang. However, it must be noted that in Mahoney's series, patients were operated via subvastus approach, which limits visualization in the posterolateral area.

Prosthetic posterior condyles implanted in this experiment were symmetric, as most TKAs available on the market. The shape of the posterior condyles has been investigated mostly in the sagittal plane[47-50] and little is known about their morphometry (symmetric or asymmetric) and their mediolateral dimensions. Recently, Monk et al.[51] analyzed a series of MRI in healthy volunteers and demonstrated that the postero-lateral condyle (mean width, 24 ±3.5 mm) was narrower than the postero-medial condyle (mean width, 26 ±3.0 mm) but further morphometric investigations are required to improve our understanding of this specific topic.

Conclusion

This work demonstrates that sizing in TKA is challenging due to the non-anatomic design of current implants. When choosing the appropriate implant size, surgeons should take into account not only the resected surface but also the implants volume. Some apparently 'normosized' TKA, in term of surface coverage could in fact be oversized in term of prosthetic volume. The clinical consequences are still unclear but they suggest that both femoro- and tibio-popliteus impingements could play a role in residual pain and perhaps limitation of flexion in TKA.

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Section IV

Conclusions: the future of TKA

Discussion

The objective of this thesis was to investigate the causes of poor results after TKA with special interest in (i) bone-implant mismatch and (ii) soft tissue-implant impingements. The series of clinical, anthropometric and experimental studies presented confirm the original hypothesis, that 'unexplained' pain after TKA could well be attributed to lack of anatomic restoration, resulting in soft tissue-implant impingements. These findings discussed hereafter have clinical implications, regarding the optimal sizing and positioning of TKA components, and provide input for the development of more soft tissue-friendly designs.

Section I

In the clinical studies, it was demonstrated that TKA fails to meet expectations of 44% of patients with regards to physical activities, of which 52% remain dissatisfied with their procedure. The literature reveals that factors associated with more painful knee arthroplasty include female gender, younger age at the time of surgery, and higher than normal depressive or anxiety states. However, such psychological speculations should not overshadow physicians' responsibilities to identify hidden mechanical causes. Surgeons should keep in mind that 'unexplained' pain does not mean 'unexplainable' pain, but mostly 'not-yet understood' pain. Moreover, a significant number of patients with apparently well-implanted and well-positioned TKA experience residual pain – hence poor perceived outcomes – attributable to overstuffing or impingements, due to slight over-sizing.

In our continuous prospective series of patients with TKA, we found that oversized components are an under-recognized cause of residual pain. CT-scan measurements revealed a mediolateral prosthetic overhang at one or more zones, in 66% of the femurs and 87% of the tibias. The pre- to post-operative improvements of the pain and function scores were significantly greater in patients without overhang, and regression and latent class analysis indicated significant negative correlations between over-sizing and outcomes.

An important finding was that apparently small details such as one or two millimeters of prosthetic overhang – hardly visible on standard imaging – can significantly jeopardize outcomes. These slight overhangs, which can occur either on the tibia or the femur, can only be identified by meticulous CT or ultrasound investigations. Their prevention remains a challenge with current TKA due to the high variability of human anatomy and to the interactions between sizing, positioning and ligament balancing, which often oblige surgeons to accept a compromise.

Section II

In the anthropometric studies, anatomic variations of the bony contours at the knee joint were found in multiple anatomic planes and to greater extents than expected, which explain the incidence of bone-implant mismatch in TKA. From a large CT database, detailed morphometric studies were conducted at the levels of standard TKA resections, and the native bone contours were compared to those of TKA models. Better functional results were observed with undersized implants at the distal femoral cut probably because classic implants do not reproduce the trapezoidal shape of the distal femur, and are excessively rectangular. Hence, surgeons find themselves obliged to slightly undersize the implant distally in order to avoid anterior overhang. The newly defined 'trapezoidicity' ratio revealed that 'rectangular-trapezoidal' variability of the distal femur should not be ignored. Most prosthetic overhangs were observed in trapezoidal femurs and most of the tested femoral implants appeared to be excessively rectangular when compared with the bony contours of the distal femur.

The influence of surgical technique on bone-implant fit at the tibia was also investigated, and another important finding was that implant positioning – orientation of resections – considerably influences the shape of the bone cuts. Therefore technique modifications such as external rotation, or varus-valgus alignment could induce bone-implant mismatch. Externally rotating the femoral component amplifies the asymmetry between the medial and lateral condyles, and exacerbates prosthetic overhang at the posterior resections, particularly in the supero-lateral zone.

The choice of aligning the tibial component to optimize simultaneously prosthetic coverage and alignment with the extensor mechanism was investigated. Aligning the component to the posterior tibial margin, the trans-epicondylar axis or the anterior tibial tuberosity axis, was found to influence perceived asymmetry and aspect ratio of the tibial plateau. The study emphasizes the great variation in tibial plateau morphology, with up to 17% of patients having a reversed asymmetry (lateral greater than medial), and illustrates that custom implants could be beneficial for extreme cases of asymmetry.

The interrelations between surgical techniques or surgical goals and implant design had never been clearly emphasized and this should be integrated in future designs. All these investigations conducted with so-called ‘classic’ implants should be redone with more recent designs.

Section III

In the experimental studies, attention was directed towards the forgotten dimension of the knee joint: the soft tissues and the knee envelope. It was hypothesized that residual pain in TKA could be due to impingements of the soft tissues against non-anatomic implants or against mal-positioned or mal-sized implants. An imaging protocol was established to enable direct visualization of the interactions between soft tissue and implants during knee flexion. This gave the opportunity to understand the consequence of TKAs on the tracking of several soft tissue but particularly the popliteus tendon, which is a high-risk structure due to its unique intra-articular location. This was a significant advance, as medical imaging seldom provides such direct vision in the presence of metallic implants, and our ability to do so enhances our 'mental representation' of the anatomy.

The principal clinical relevance of the experimental studies is that both femoro- and tibio-popliteus impingements could play a role in residual pain and perhaps in limitation of range of motion after TKA. When choosing the appropriate implant size, surgeons should take into account not only the resected surface but also the implant volume. Some apparently 'normosized' TKA, in term of surface coverage could in fact be oversized in term of prosthetic volume. Following our findings, painful TKA have been successfully treated with arthroscopic popliteus tendon release, after arthroscopic visualization of a tibio-popliteus impingement (Figure 1).

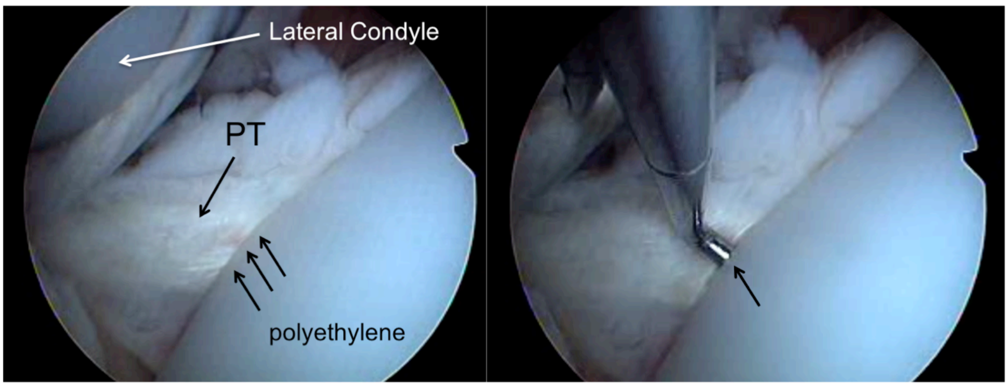

Figure 1: *Arthroscopic view of a tibio-popliteus impingement in a well-sized right TKA.*

This experimental analysis focused mostly on the role of the popliteus tendon due to its intra-articular position and its vulnerability with regard to the prosthetic implants. However, other anatomic structures such as the iliotibial band, the patellar and quadriceps tendon and the medial collateral ligaments could be investigated. Also, it is unclear whether our findings obtained with one specific kind of prosthetic kinematics, could be different with other categories of implants such as medial pivot or posterior cruciate retaining TKA.

Conclusion

The main theme of this work was the analysis of the interactions between the soft tissue surrounding the knee joint and the prosthetic components in TKA. Surprisingly this topic had never been deeply investigated in medical literature, despite thousands of investigations concerning *'TKA outcomes'*. It is probably because soft tissues are not visible through static medical imaging commonly used after TKA, that the general representation of the knee, for arthroplasty surgeons, is limited to bones and ligaments and that we omit to have a dynamic vision including the joint capsule and all other surrounding tissues. Even recent *'digital knee models',* which mimic weight-bearing and flexion-extension, include a small number of muscles and tendons, limited to insertions and force direction, far from representing the normal anatomy.

Over the past decade, research and development initiatives for TKA have focused on a multitude of innovations utilizing sophisticated computer technologies, to improve sizing and positioning of implants. Such technologies include surgical navigation and robotics, patient-specific instruments and custom-made implants, though their efficacy at reducing residual pain and improving outcomes remains debatable. The use of unicompartmental and patellofemoral implants, isolated or in combination, could be a solution to avoid bone-implant mismatch and preserve native knee kinematics, despite technical challenges that they pose to surgeons.

The findings from the series of studies presented in this thesis confirm the existence of considerable anatomic variations in human knees that are not matched by contemporary TKA designs. The resulting prosthetic overhang and/or under-coverage are a common cause of soft tissue impingements that result in residual pain and compromise knee function. Surgeons should beware of the consequences of bone-implant mismatch in order to prevent, diagnose and treat soft tissue impingements. Manufacturers should also acknowledge the anatomic variations in order to enhance the design of their implants and instruments to anticipate and avoid prosthetic overhang without compromising bone coverage and implant fixation.

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