Biomechanics of the knee

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Abstract

In this article the biomechanics of the tibiofemoral joint, patellofemoral joint and menisci are discussed. Normal knee kinematics depend on soft tissue and bony structures working closely together. Implant manufacturers have considered this interaction in order to design and develop a broad spectrum of total knee replacement (TKR) implant solutions. These designs include anatomic and functional considerations, asymmetric or symmetric implants, mobile or fixed bearing offerings and 'high flexion' designs, as well as designs with a single or multiple radii of curvature. Substantial differences in outcome between these designs remains unproven and TKR design selection at present is therefore often based on other factors, such as cost and the surgeon's familiarity with a particular knee system. An understanding of knee biomechanics pertaining to implant design will help surgeons with implant selection and help refine the method of implantation to optimize patient outcomes.

Keywords implant design; knee biomechanics; knee kinematics; meniscus; patellofemoral joint; total knee replacement

Introduction

The native knee is a synovial joint that functions as a complex hinge whilst also permitting rotational, anteroposterior and medial/lateral translational movement with 6° of freedom. Our understanding of the biomechanics and kinematic profile of this complex articulation has been progressively augmented through *in vivo* and *ex vivo* dynamic and static studies dating back to 1836[1]. The bony morphology offers little stability in this joint. Understanding the close interaction between bones, ligaments, capsule, musculotendinous structures and menisci has helped our understanding of the importance of these structures in conferring stability and how pathological processes involving any of these can result in biomechanical abnormalities of the knee. An in-depth understanding of this interaction is also vital in the development of knee implants and the ongoing quest to improve outcomes in knee arthroplasty.

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Tibiofemoral joint

Anatomy

The knee may be considered to consist of three compartments: the patellofemoral joint (PFJ), and the medial and lateral tibiofemoral compartments. The tibia and femur are described as asymmetrical with regard to their bony geometries. The femoral condyles vary with regard to their size and extension distally, with the medial femoral condyle lying more distal and being larger in comparison with the lateral femoral condyle. The tibial plateaus are asymmetrical in the sagittal plane, with the medial tibial plateau (MTP) concave and the lateral tibial plateau (LTP) convex, respectively. This asymmetry of the femoral condyles and tibial plateaus enables the tibia to rotate around its anatomical axis whilst the knee is flexing. The MTP has a sloped anterior surface with a posterior surface that is horizontal. The LTP's articular surface is horizontal. However, anterior and posterior to this surface, the surfaces slope downwards to accommodate the anterior and posterior horns of the lateral meniscus. The menisci, discussed later, are of key importance in improving the congruency of the tibial plateau with the femoral condyles.

Geometry and alignment

The weight-bearing axis describes the normal 'frontal alignment' of the knee in the coronal plane. It extends from the centre of the hip down to the centre of the ankle. Understanding this principle helps define varus and valgus malalignment (Figure 1).

Normal sagittal plane alignment is defined by the location of the centre of the knee lying just posterior to the weight-bearing axis. The resultant extension moment is resisted to some extent by muscular activity but mainly by the posterior knee capsule and ligaments. In hyperextension deformities, the centre of the knee is located more posterior than normal, whilst in flexion deformities, it is located anterior to the weight-bearing axis.[2]

Kinematics

Rigid four-bar linkage theory: previously, the kinematics of the knee had been considered to result from a 'rigid four-bar linkage'.[3] By means of a construct allowing a mixture of femoral rolling and slide, this theory was considered the basis of how the knee can achieve deep flexion. The 'rigid four-bar linkage' mechanism is based on four linked bars two of which are the cruciate ligaments and the other two are the lines connecting their insertion points on the femur and tibia (see Figure 2). The limitations of this theory however became apparent and several reasons were identified. Firstly the movement of the knee is limited to a two-dimensional projection in this model when in fact it is multi-planar. Moreover, the ligaments are not rigid and there is variable tension in different bundles of the cruciates at different degrees of flexion.

Rollback, slide and rotation: freeman and Pinskerova[4] used dynamic MRI to further the understanding of knee kinematics by demonstrating the concept of anteroposterior movement and rotation taking place to differing degrees across the medial and lateral tibiofemoral compartments.

Medially, in full extension, the anterior surface of the femoral condyle articulates with the tibia. At approximately 20° of

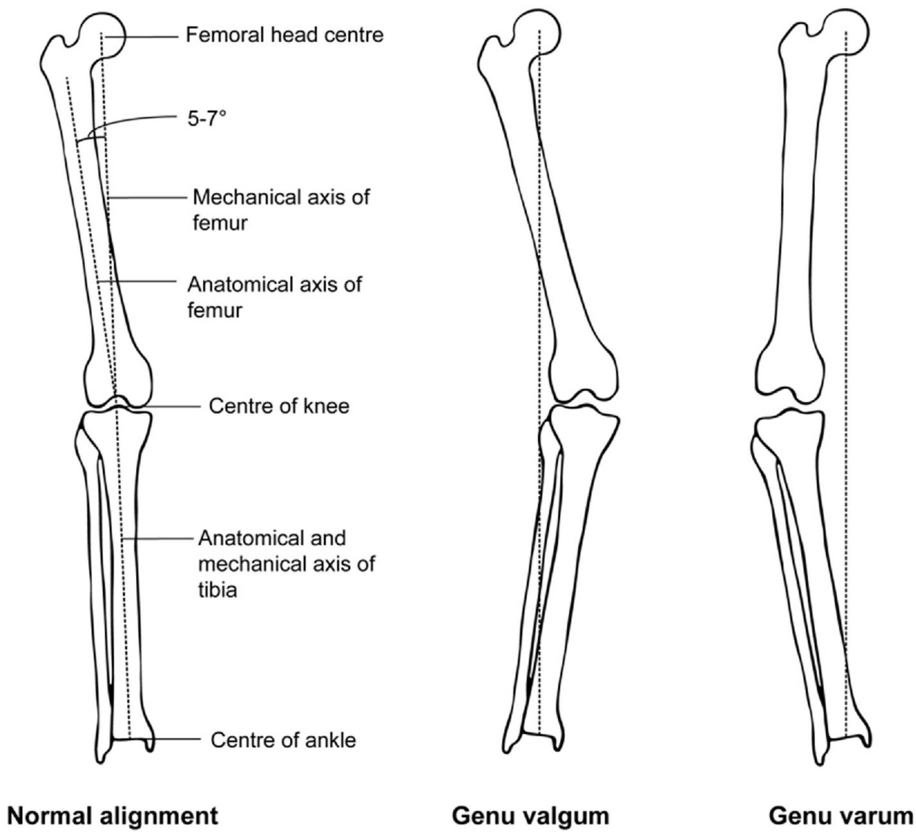

Figure 1 Diagram showing the various axes of the femur and tibia along with varus and valgus malalignment.

flexion, the femur 'rocks' to articulate through the posterior condylar surface. The medial femoral condyle has limited anteroposterior movement with flexion to 110° through a mixture of posterior cruciate ligament (PCL) mediated rollback and slide. Here, the excursion of the contact point between the femoral condyle and tibia is 1 cm only and this is due to the concave nature of the tibial plateau and relatively fixed medial meniscus anteroposteriorly (see Figure 3).

Laterally, the excursion of the contact point between the tibia and femoral condyle is longer at 2 cm, secondary to a more mobile lateral meniscus and a convex tibial plateau. In full flexion, the contact point is seen to be located between the tibia and posterior horn of the lateral meniscus. This asymmetry in movement between the two compartments results in 30° of axial rotation during flexion, of lateral compartment rotation around the medial compartment and therefore internal rotation of the tibia relative to the femur. Biomechanically, there are two functions of 'femoral rollback' in flexion. Firstly, it increases the lever arm of the quadriceps and secondly, it allows the femur to clear the tibia. Conversely, the lever arm of the hamstrings is increased during knee extension as the femur rolls forwards, thus allowing control and prevention of hyperextension.

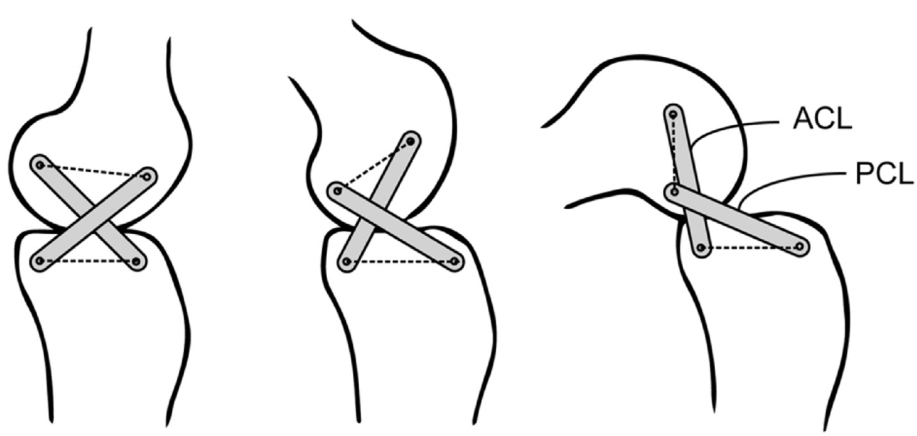

Figure 2 Diagram showing the four-bar linkage construct formed by the anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), a line connecting their femoral attachments and a line connecting their tibial attachment.

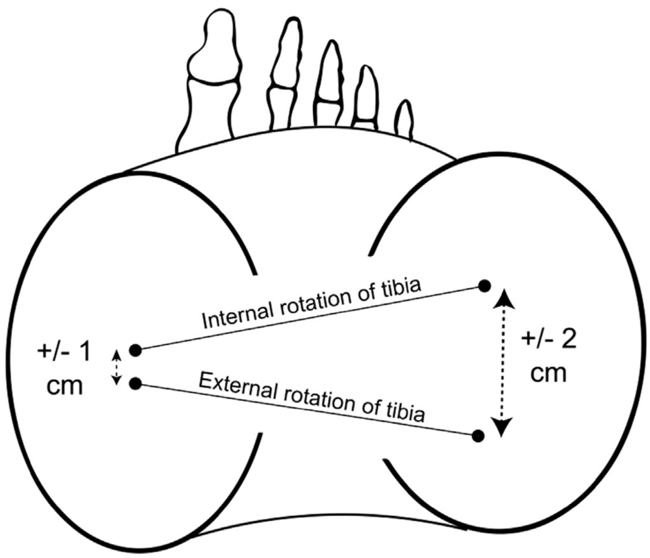

Figure 3 Diagram showing the movement of the contact points of the femoral condyles on the tibial articular surface as the knee flexes and extends.

Screw-home: the screw-home mechanism describes the final arc of external rotation of the tibia relative to the femur when the knee moves from flexion to extension. It is at this point that the cruciate ligaments are at maximum tightness and the knee is conferred maximal stability. Conversely, the knee rotates internally during flexion and this is initiated by the popliteus. As a result, the knee 'unlocks' and internal rotation of the tibia relative to the femur can continue through the mechanisms described above.

Static and dynamic restraints

Restraints to knee movements are divided into static and dynamic. Static restraints include the bony articulations, the geometry of articulating surfaces and the connecting ligaments. The dynamic restraints around the knee are the muscles surrounding the joint and their co-ordinated activity. Ligaments, particularly the cruciates, have a proprioceptive function as well, which is key in moderating the movement of the knee through its range of motion. The ligaments which stabilize the knee are summarized in Table 1.

Anterior cruciate ligament (ACL): the ACL consists of two bundles separated by the intercruciate band, inserting either-side of the bifurcate ridge on the lateral wall of the femoral notch and named on the basis of their tibial insertion; the anteromedial and posterolateral bundles. The former is tighter in flexion, the latter in extension. The anteromedial bundle is also predominantly an anterior restraint and can be tested by the Lachman test whereas the posterolateral bundle restricts rotation and is evaluated through pivot shift testing. The ACL has a further role in resisting varus, valgus and rotational forces as shown in Table 1.

Posterior cruciate ligament (PCL): the PCL is also composed of two bundles: the anterolateral and posteromedial bundles. Its primary action is to resist posterior translation of the tibia relative to the femur. At full flexion the posteromedial bundle provides most resistance to posterior translation while at 90° of flexion the anterolateral bundle is more taut. The PCL's secondary function is to provide rotational stability, particularly resisting internal rotation between 90° and 120°.[5] Understanding the anatomy and role of the PCL is important in implant design, as some retain the PCL and aim to restore its tension and configuration while others sacrifice the PCL and aim to reproduce its function using a femoral cam component as discussed later.

Summary of the knee stabilizers by movement[2]

Movement	Primary restraint	Secondary restraint
Anterior translation	Anterior cruciate ligament (ACL)	Iiotibial band: 24% Mid-medial capsule: 22%. Mid-lateral capsule: 20%. Medial collateral ligament (MCL): 16%. Lateral collateral ligament (LCL): 12%. Menisci.
Posterior translation	Posterior cruciate ligament (PCL)	LCL
Varus	LCL	ACL Posterolateral complex (PLC)
Valgus	Superficial MCL PMC full extension	ACL
Internal rotation	ACL PCL (between 90° and 120°)	Posterior oblique ligament (POL) Posteromedial complex (PMC)
External rotation	Popliteofibular ligament LCL Posterolateral complex at 30° of flexion	MCL (all degrees of flexion)

Table 1

Patellofemoral joint

Anatomy

The patella has a vital function to augment the mechanical advantage of the quadriceps by increasing the moment arm. It is the largest sesamoid bone in the body. Proximally, the quadriceps tendon inserts into and envelopes it, and more distally, the patella tendon does the same. It has seven facets in total, which are located on the proximal two-thirds of the patella. Three of these are found medially, another three laterally and the final facet is on the medial border of the patella. This facet articulates with the medial femoral condyle in deep flexion. The trochlea of the femur acts as the bony restraint for the PFJ. The lateral femoral condyle is more anterior compared to the medial side and the sulcus of the trochlea is deeper distally, thus providing a groove in which the patella articulates. The trochlea contains a medial and lateral facet. The medial patellofemoral and patellotibial ligaments (MPFL/MPTL) are also important static stabilizers of the PFJ whereas the vastus medialis oblique (VMO) muscle is the main dynamic stabilizer.

Geometry

Both components of the PFJ exhibit potential variability in their geometry. The implication of a smaller patella medial facet include patellar instability and higher contact stresses across the joint, thus increasing the likelihood of developing osteoarthritis.[6] Meanwhile, the depth of the trochlea is determined by the sulcus angle, which is the angle between a line drawn from the highest point of the medial femoral condyle to the trochlear sulcus and a second line from the highest point of the lateral femoral condyle to the trochlear sulcus. The geometry of the trochlea has also been classified by Dejour and this is based on lateral radiographs and axial CT or MRI imaging.[7] Higher sulcus angles and Dejour's grades of trochlear dysplasia are both pre-disposing factors for patellar instability.

Alignment and malalignment

Alignment of the patella in the coronal plane is determined by the Q angle. This is the angle subtended by intersecting lines from the anterior superior iliac spine (ASIS) to the centre of the patella and the centre of the patella to the tibial tubercle. A normal angle ranges between 5° and 20° and is higher in females as compared to males. However, an angle greater than 20° is associated with PFJ instability and pain. Alignment is also assessed by the tibial tuberosity-trochlear groove distance, measured by superimposing two axial CT or MRI images. A distance of more than 20 mm is considered to be a risk factor for instability.[8] Operative solutions to restore the biomechanics of the knee in such cases may include a medial transfer of the tuberosity. In scenarios where the trochlea is shallow, trochleoplasty can be considered. Patella height is of key importance regarding stability of the patollofemoral articulation, as it dictates the point in the flexion arc at which the patella engages with the trochlea. Consideration of correction of patella height (distalisation) should be given when contemplating reconstruction of the PFJ for instability.

Medial patellofemoral ligament and patella stability

The medial patellofemoral ligament (MPFL) is an important static stabilizer of the patella and has been demonstrated to contribute to approximately 53% of the resistive force when the patella displaces 12.7 mm laterally.[9] It is formed by capsular fibers and originates from the medial femoral epicondyle and partially from the superficial MCL. It inserts into the superomedial patella and varies in shape and size between individuals. It is commonly disrupted in recurrent dislocations and can be reconstructed in cases that have failed conservative measures where bony anatomy is largely normal.

Patellofemoral joint kinematics

The MPFL and VMO interdigitate approximately 20–30 mm proximal to the MPFL insertion into the patella. This intertwining shortens the fibers, which in turn pulls the patella medially within the trochlear groove as the knee flexes between 20° and 30°.[9] The patella is not constantly placed within the femoral sulcus. Its position is dynamic and also involves rotation. Initial engagement occurs at 20° of knee flexion when the distal part of the patella makes contact first. It subsequently tracks along a conforming groove through progressive flexion and, as this occurs, the contact area of the patella shifts proximally. Beyond 90°, the patella tilts laterally. PFJ contact stresses gradually increase with progressive flexion. As hyperflexion occurs, the patella lies in the intercondylar groove.[10]

Menisci

Meniscal anatomy

The medial and lateral menisci are fibrocartilagenous, crescent-shaped structures which have concave superior surfaces (to allow articulation with the convex femoral condyles) and flat inferior surfaces to accommodate the tibial plateaus. The menisci are composed primarily of water (72%) and collagen (22%) with cells interposed.[11] Meniscal cells synthesize the collagen as well as proteoglycans, glycoproteins and non-collageneous proteins which make up the extracellular matrix.

Medial meniscus: this is semicircular structure which has an anteroposterior diameter of approximately 35 mm. It is also wider posteriorly compared to anteriorly. It is attached anteriorly to the tibial plateau just anterior to the ACL within the intercondylar fossa, though this does vary. Posteriorly, it is attached between the lateral meniscus and PCL, into the posterior intercondylar fossa. There are three key ligaments associated with the medial meniscus; the coronary Ligament, which attaches its peripheral border to the joint capsule, the deep MCL at the midpoint, attaching via a condensation in the joint capsule, and the intermensical ligament, which is a fibrous band of tissue connecting the anterior horn of the medial meniscus and the lateral meniscus.

Lateral meniscus: in comparison to the medial meniscus, this is almost circular. Furthermore, it has a more or less a uniform width anteriorly and posteriorly. It is more mobile compared to the medial meniscus and occupies a larger surface area of the articulating surface. Its anterior insertion lies anterior to the intercondylar eminence and adjacent to the ACL's broad attachment site. The posterior horn inserts at its root further anterior to the insertion of the medial meniscus' posterior horn and posterior to the lateral tibia spine. The lateral meniscus does not attach to the lateral collateral ligament and is loosely attached to the capsular ligament. Its posterior horn is attached to the medial femoral condyle via the anterior meniscofemoral (Humphrey) and posterior mensicofemoral (Wrisberg) ligaments.

Meniscal kinematics

Excursion: a varying degree of movement occurs between the medial and lateral mensici, with a range between 3 mm and 5 mm for the medial meniscus and 9 mm to 11.2 mm in the lateral meniscus. The key difference between the two sides is that the lateral meniscus moves as a single body whilst the posterior horn of the medial meniscus is much more tethered due to the meniscotibial portion of the posterior oblique ligament. This can lead to increased risk of tears posteromedially with consequential trapping of fibrocartilage during flexion.

Meniscal functions

Load transfer and peak contact stresses: the menisci are vital in transferring loads. As a person weight-bears, this produces axial forces across the knee. This leads to compression of the menisci resulting in circumferential or hoop stresses. These forces are converted into tensile forces along the circumferential collagen fibers of the meniscus. It has been reported that 50% of the load in the medial compartment and 70% of the load in the lateral compartment are transferred via the menisci (Figure 4). If the medial meniscus is removed, there is an up to 70% reduction in femoral condyle contact area and a 100% increase in contact stress. Removal of the lateral meniscus on the other hand results in a 50% decrease in contact area and a 200−300% increase in contact stress in the lateral compartment and is thought to contribute to faster articular cartilage degeneration in this compartment.[11]

Stability and shock absorption: another biomechanical function of the meniscus is to confer joint stability. A medial meniscectomy in an ACL intact knee does not have major implications on anteroposterior translation. However, when the ACL is not intact, the lack of a medial meniscus increases tibial translation by 58% when the knee is flexed to 90°.[12] The menisci also act as shock absorbers and it has been demonstrated that in knees without menisci, the shock absorbtion capacity reduces by 20%.[13] Moreover, mechanoreceptors identified within the middle and outer parts of the anterior and posterior horns of menisci, give menisci a proprioceptive role as well[11]

Knee kinematics and implant design

Knee osteoarthritis is a leading cause of joint pain and disability, with an exponentially growing global incidence. In severe cases of tricompartmental disease, where conservative measures have failed, total knee replacement (TKR) is a recognized treatment as it has proved to be a successful procedure offering increased knee function and reliable pain relief. The current demand for TKR is rising and the number of knee replacements annually has surpassed that of total hip replacements. Co-incident with improving understanding of knee joint kinematics, the design of TKRs has developed over the last 45 years.

Single versus multiple radii

In 1971 the concept of the instant centre of rotation was introduced by Franklin.[14] He showed that as one rigid body rotates around the other, there is a point with zero velocity at any given moment in time called the instant centre of rotation. Due to both bony morphology and soft tissue restraints he established that the instantaneous centres for successive positions of the links of the knee move. This work was based on true lateral X-rays of the knee which reduced knee movements to a two-dimensional projection. This was similar to other early studies including Menschik's four bar linkage theory discussed earlier which also used two dimensions when representing the cruciates.[3]

Based on Franklin's work on the moving centre of rotation, traditional bi-condylar TKRs including commonly used implants in the market today were designed with multiple radii of rotation (see Figure 5). With the advent of technology such as magnetic resonance imaging, the three-dimensional reality of knee motion was assessed and the existence of multiple instantaneous centres of knee flexion/extension was challenged. Hollister's[15] work among others suggested a single flexion/extension axis during functional flexion of the normal knee and consequently, single radius (SR) designs have been developed. The theoretical benefits include larger articulating contact areas and lower contact loads, collateral ligament isometry providing enhanced stability throughout the range of flexion and an extended quadriceps moment arm.

Anatomic versus functional approach

The anatomic philosophy of TKR focusses on implants that preserve one or both cruciate ligaments. Motion is soft tissue guided or 'accommodative', whereby the ligaments and tissue help drive the kinematics of the knee in combination with bone. 'Cruciate-retaining' prostheses developed from this concept. Here the PCL, which functions to pull the femur posteriorly relative to the tibia as the knee is flexed, is preserved. Some CR prostheses consisted of a relatively flat surface in the sagittal plane whereas others kept a more congruent surface. In reality, however, paradoxical motion has been reported to occur in CR implants where the femur translates posteriorly relative to the tibia during extension and anteriorly relative to the tibia during flexion leading to impingement and loss of flexion[16](Paradoxical 'roll forward'). In an attempt to re-create a kinematic profile more closely resembling the native knee, a bi-cruciate-retaining (BCR) implant design has developed. Although fluoroscopic analysis has shown near-normal kinematics in BCR knee replacements[17] the patients pre-operative anatomy may not be replicated. In order to achieve this, the implant can be aligned according the patient's own coronal plane kinematic profile, which can be defined as 'kinematic alignment'. Studies have shown improved functional outcomes in TKRs with kinematic alignment but this must be tempered by the risk of malaligned 'outliers' with the theoretical likelihood of early failure, as recreating the patient's natural alignment can be challenging and may result in component malalignment.[18]

Advocates of the functional approach attempted to simplify TKR biomechanics by removing both ACL and PCL. In this design philosophy, the implants, as opposed to the soft tissues, drive the

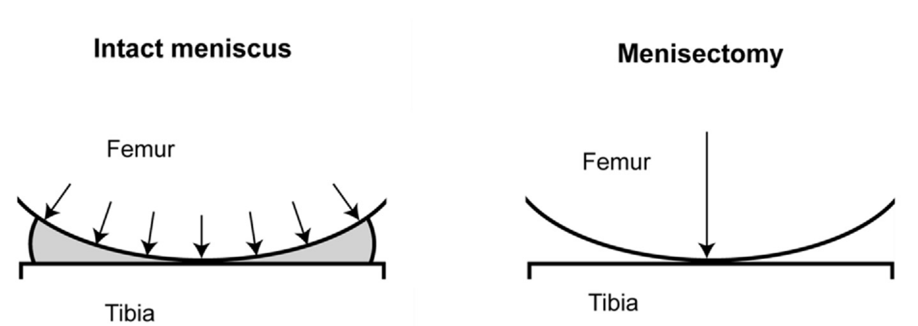

Figure 4 Diagram showing articular contact stresses before and after removal of the meniscus. The reduced surface area of contact leads to increased contact stresses.

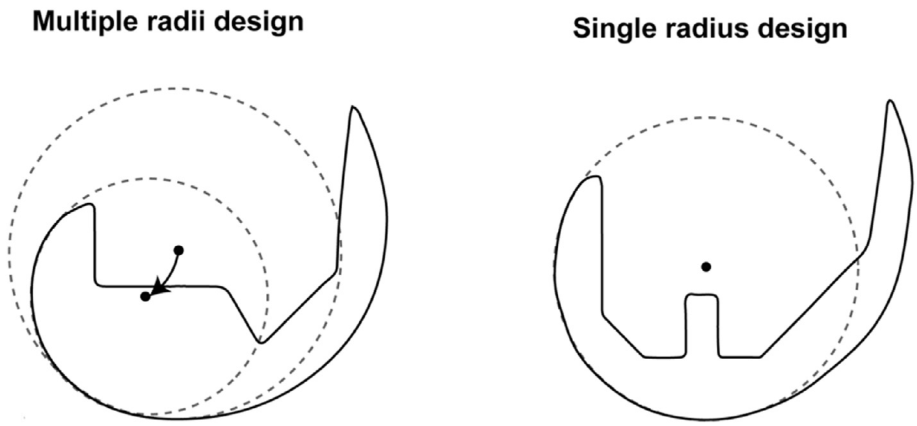

Figure 5 Examples of total knee replacements with a multiple radii design (left) and a single radius design (right).

kinematics of the knee. In 1978 Insall and Burstein designed a knee arthroplasty implant in which the posterior cruciate ligament was replaced by a femoral cam component which connected with a tibial post at about 70° of flexion, allowing the femur to 'roll-back' thereby increasing flexion. Although this posterior stabilized (PS) implant reduced anterior femoral subluxation associated with early CR designs, it did not completely restore normal femoral rollback characteristics.[19] Recent implant designs have included the bicruciate substituting (BCS) TKR utilising a tibial post with two femoral cams to substitute for both ACL and PCL mediated control of sagittal plane position. The added anterior femoral cam is designed to prevent excessive posterior movement of the femur on the tibia in order to more closely restore native anteroposterior translation.

Implant driven motion is also the goal in medial pivot knee replacement designs. These medial SR designs employ a deeper, highly congruent medial compartment to allow rotation and a less congruent lateral compartment permitting posterior translation of the lateral femoral condyle. This is kinematic philosophy aims to mimic the natural femoral rollback and rotation described by Freeman and Pinkserova.[4]

High flexion knee designs

Range of motion is an important factor in ensuring patient satisfaction in knee arthroplasty. Implant design, as well as patient factors and surgical technique, contribute to high flexion. Fluoroscopic kinematic analysis has shown that for every 2 mm decrease in posterior condylar offset, the maximal obtainable flexion decreases by a mean of 12.2°.[20] To attain motion ranges similar to the native knee, designers have offered femoral prostheses with both increased posterior femoral condylar offset and shortened posterior condyles (to improve 'clearance' in deep flexion. Such designs also aim to achieve a larger contact area during high flexion thus theoretically reducing contact pressures and wear. Other implant features designed to improve flexion include an oblique cut in the anterior margin of the tibial component and a deep femoral trochlea to help reduce extensor mechanism impingement. Further designs currently offered include femoral implants which have progressively increasing radius of curvature which introduces further challenges in flexion gap balancing. Despite the theoretical kinematic profile which an implant solution may offer, further studies with long term follow up are yet to determine whether these designs correspond to better functional patient outcomes, including range of motion.

Asymmetric versus symmetric

Symmetry in TKR design is related to trochlear geometry. Asymmetric femoral components have a trochlear groove in line with the longitudinal axis of the femur. Although long-term results for aseptic loosening of the tibial and femoral components have been shown to be excellent, some implants have had a 4−15% rate of patella-femoral complications such as subluxation, fracture or dislocation.[21] To tackle this issue, some designs have been altered to a 'symmetrical' femoral component, which have a trochlear groove perpendicular to the flexion−extension axis of the knee. The trochlear grooves of many modern designs have also been deepened, laterally flared and flattened to improve tracking and congruency with the patella. This feature of modern knee arthroplasty design is likely to reduce symptoms of pain and instability from the patellofemoral joint post arthroplasty and may change the threshold to resurface the patella for some surgeons.

Mobile versus fixed bearing

'Conformity' in TKR design is defined as the difference in the radii of the tibial and femoral articulating surfaces in the sagittal or frontal plane. Conformity has a conflicting impact on native knee kinematics and contact stresses. A highly conforming design decreases contact stress and hence polythene wear but restricts movement and therefore adversely affects normal knee kinematics. A low conforming design however results in high contact stresses, much like a meniscectomized knee (see Figure 4) but allows more normal knee kinematics.

TKR design may prioritize one parameter (contact stresses or native knee kinematics) at the expense of the other. Prostheses with mobile polyethylene bearings were developed to address this 'kinematic conflict'. These designs have a highly conforming articulation between the femur and polythene to reduce contact stresses while maintaining more normal knee kinematics through antero-posterior as well as axial rotation at the polythene tibial interface. Some surgeons also feel that the tibial component is easier to implant in these designs, as it is less sensitive to rotational malalignment through the polythene bearing's ability to self-correct. Some of the potential concerns of these designs, however are the potential for polyethylene fracture, backside wear and subluxation or dislocation of the meniscal-bearing due to instability secondary to decreased coverage of the proximal tibia.[22] The theoretical reduced wear and loosening in the long term with a mobile bearing design philosophy must be offset with the potential for of failures due to polythene wear, subluxation or dislocation.

Conclusion

Our understanding of how the native knee functions and moves has become progressively more advanced and this is partly due to the development of more sophisticated imaging technology in recent years. We note that normal knee motion depends on many structures, each with specific roles, acting in harmony. This kinematic understanding has been used by implant manufacturers to continue to innovate and the result is a wide spectrum of TKR implant designs with varied kinematic philosophy. Substantial improvements in outcome, however, remain unproven and controversy surrounding prosthestic design continues to exist. Design selection today is often based on other issues such as cost, availability and the surgeon's familiarity with a knee system and technique.

TKR implant design will remain an area of highly active research as we face the new challenges of today's patient demographics. More and more patients live longer, are physically active and are operated on sooner, placing more demand on TKR durability and challenging satisfaction. Further innovations such as robotic-assisted surgery with the potential to significantly improve implant alignment accuracy are coming into clinical use. Their influence on clinical outcome remains unknown and as more data is published we could see wider recognition of this and other new innovations in knee arthroplasty. ◆

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