Alignment in total knee replacement

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The advent of computer-assisted knee replacement surgery has focused interest on the alignment of the components. However, there is confusion at times between the alignment of the limb as a whole and that of the components. The interaction between them is discussed in this article. Alignment is expressed relative to some reference axis or plane and measurements will vary depending on what is selected as the reference. The validity of different reference axes is discussed. Varying prosthetic alignment has direct implications for surrounding soft-tissue tension. In this context the interaction between alignment and soft-tissue balance is explored and the current knowledge of the relationship between alignment and outcome is summarised.

Three challenges must be met to produce an acceptable result from a knee replacement, namely perfect alignment of the components, good soft-tissue balance and compatibility between the femorotibial articulation and the quadriceps mechanism. The surgeon seeks to produce a replacement which is ideally aligned in the coronal, sagittal and axial planes, with the femoral component matched to the tibial in rotation, with a joint line at the appropriate level, with the soft tissues balanced in flexion and extension and tensioned sufficiently to produce stability, but without limiting the range of movement or producing excessive compression on the polyethylene, and with the patella tracking in the correct plane. This is a daunting task. All the variables listed interact so that a small error in one parameter can produce considerable changes in the others. There is a paucity of information on the quantitative aspects of any of them and we are only just beginning to develop surgical techniques which can control them with accuracy. To date, we have made progress by using an intuitive approach and this has paid considerable dividends. We have refined total knee replacement (TKR) to the stage at which it produces good, but not perfect, relief from pain and reasonable, but not outstanding, function. The current standards will not suffice in the future because the expectations of our patients and the mechanical demands on knee prostheses are increasing.

The recent concentration on alignment and the development of computer-assistance technologies have opened a new pathway to progress. We now have accurate and quantitatively defined control over several of the important parameters of a replacement. We can set up outcome studies using this information. Now that we have control of some of the variables we can begin to manage the others in a similar fashion. This article attempts to summarise our current knowledge of the requirements for alignment in TKR and explores how alignment interacts with some of the other variables which must be considered.

Parameters of alignment

Alignment is relative. The position of a prosthetic component is adjusted relative to another component or to a defined but theoretical construct, an axis or a plane. In TKR there are two separate concepts of alignment, that of the limb as a whole and that of the component. We reference alignment to either theoretical constructs or anatomical landmarks. The theoretical axes are the mechanical axes of the limb and that of the femur and the tibia. The mechanical axis of the limb (Fig. 1) represents the entire limb from the hip to the ankle and is a straight line drawn from the centre of the femoral head to the centre of the ankle. It can be measured with appropriate software very accurately (to within 1°).1 From the perspective of the knee its path is determined by intra-articular and extra-articular factors. The most common demonstration of the mechanical axis of the limb is the standing Maquet view.2 The mechanical axis of the femur is a straight line from the centre of the
femoral head to the middle of the intercondylar region. The mechanical axis of the tibia is a straight line from the centre of the tibial plateau to the middle of the ankle (Fig. 1). In a mechanically-neutral limb the mechanical axes of the femur and tibia lie along that of the limb. These axes are applicable in the coronal and sagittal planes.

There are many anatomically-based reference lines and planes which are used in TKR. For alignment of the femoral component these include the distal one-third of the medullary canal of the femur, the anterior cortex of the femur, the intercondylar groove of the femur and the plane of the posterior parts of the femoral condyles. For alignment of the tibial component there are the upper two-thirds of the medullary canal of the tibia, the anterior cortex of the tibial flare and lines connecting the posterior cruciate ligament variable parts of the tibial tuberosity. Unfortunately, all the anatomical reference systems show a wide degree of inconsistency, with the exception of Whiteside’s line.

The transepicondylar axis of the femur is unique in being both the mechanical axis around which knee flexion occurs and being clearly defined by anatomical landmarks. It therefore falls into both the mechanical and anatomical groups.

The third reference system is soft-tissue tension. It is used by some to position the femoral component. This is a hybrid approach in which the position of the tibial component is determined by reference to the mechanical axis of the tibia and the femoral component is placed according to the position which the femur assumes when soft tissues are stretched. It is the basis of the Oxford (Biomet UK Ltd, Swindon, United Kingdom) and LCS (DePuy Mitek Inc., Raynham, Massachusetts) Knees.

Reviews of the literature have shown a wide variability in the reference systems used both during TKR and in the subsequent analysis of alignment. Any report which deals with alignment needs to be interpreted with regard to the reference axes which have been used. Thus, reporting the sagittal alignments of the femoral component will produce different results depending on whether the reference axis is the mechanical axis of the femur, the medullary canal or the anterior cortex of the femoral shaft.

The mechanical constructs provide more rational, reproducible and consistent references than the anatomical alignments. There is debate about the relative accuracy of the soft-tissue reference system relative to the other two. Direct comparisons suggest that it is not as reliable as using mechanical reference axes, although this view has not been tested by a well-controlled clinical trial. The surgical technique on which it relies provides reasonable results, but the resultant longevity of the implant is no better than that achieved by using the mechanical constructs as reference axes.
Dimensions

A knee replacement should have technical success in six dimensions. The first three are the coronal, sagittal and axial planes and static alignment needs to be correct in all of them. The fourth dimension is the proximodistal positioning of the implant. In addition, these positions have to reflect the appropriate kinematics, both weight-bearing and non-weight-bearing, and the whole construct needs to be stable in time which is expressed as longevity.

The alignment of each component has to be controlled in three planes (coronal, sagittal and axial). There is universal agreement that in the coronal plane both the femoral and the tibial components should lie along the mechanical axis of the bones. If this is achieved, and if there is no extra-articular deformity, this will produce a mechanical axis of the limb which runs through the centre of the component. In the sagittal plane the mechanical axes of the femur and tibia are also the appropriate reference axes. In the axial plane the transepicondylar axis of the femur is used to assess rotation of the femoral component because it is the functional axis of flexion.\(^5\) The alternative is to use the intercondylar groove of the femur which is at right angles to the transepicondylar axis of the femur. This is the anteroposterior axis. There is good, but not perfect,\(^6\) agreement between the two. The posterior condylar axis should not be used since it is too variable.\(^7,8\) For the tibia, finding a suitable axis of reference for the axial plane is difficult since none of those proposed has been shown to be reliable.\(^9\) This has resulted in the widely-held view that the position of the tibial component in rotation should be that which best

<table>
<thead>
<tr>
<th>Plane</th>
<th>Component</th>
<th>Displacement</th>
<th>Joint space change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Medial</td>
<td>Lateral</td>
</tr>
<tr>
<td>Coronal</td>
<td>Femoral or tibial</td>
<td>Varus angulation</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Valgus angulation</td>
<td>-</td>
</tr>
<tr>
<td>Sagittal</td>
<td>Femoral</td>
<td>Anterior</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Posterior</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Proximal</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Distal</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Tibial</td>
<td>Post slope increase</td>
<td>0</td>
</tr>
<tr>
<td>Axial</td>
<td>Femoral</td>
<td>Internal rotation</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>External rotation</td>
<td>+</td>
</tr>
</tbody>
</table>

Table I. Summary of the impact of variations in, and by implication the bone cuts of components on the alignment and the gaps produced (+, indicates an increase in gap, -, a decrease and 0, no change)
aligns with the femoral component or femoral landmarks.6,10,11

The interaction of alignment and soft-tissue balance

It is important to achieve correct tension of the periarticular soft tissues for optimum function of a knee replacement. It must be adequate to prevent the joint from subluxing or dislocating, but high tensions may cause excessive wear of polyethylene or even limit movement. Currently, we do not know the tensions which should be achieved in the various soft tissues around the knee. It is widely assumed that there should be a uniform tension around the circumference of the knee which should be maintained in both flexion and extension. This is the concept of soft-tissue ‘balance’. There is very little direct evidence to support this view. Certainly, tensions are not uniform in the normal knee or after resection of the anterior cruciate ligament.12 Furthermore, symmetrical gaps will only cause symmetrical tensions when a femoral component of a single radius is implanted. Irrespective of whether ‘ligament balance’ is fact or fiction it is important to realise that the placement of the components affects the tensions in the soft tissues. The complexity of the interactions is summarised in Table I.

In the coronal plane a valgus femoral or tibial cut will increase the laxity of the lateral compartment (Fig. 2). If both cuts are valgus or varus the laxity will be greater being the sum of the two errors. If one is valgus and the other is varus the laxity will be symmetrical, but there will be a sloping joint line.

In the sagittal plane the slope of the tibial component affects the balance between flexion and extension gaps (Fig. 3). Increasing the posterior slope reduces the extension and increases the flexion gaps. Decreasing or reversing the slope produces tight flexion and lax extension. In the flexed knee, moving the centre of rotation of the femoral component by either displacing the prosthesis in the anteroposterior plane or by changing its size, will affect the flexion but not the extension gap (Fig. 4). Movement of the femoral component proximally will increase the extension gap without changing the flexion gap.

Femoral axial misalignment affects not only the patellofemoral relationships but also the coronal laxity in flexion. Internal rotation of the femoral component will result in lateral condylar lift-off at 90° of flexion (Fig. 5). However, this is not easy to detect at surgery because the dislocation or retraction of the patella tightens up the lateral side in a non-representative manner. External rotation of the femur will cause medial condylar lift-off and varus coronal laxity in flexion.

If soft tissue releases are indicated and performed in the well-aligned knee, and no structures of functional importance are destroyed, the effect will probably be beneficial. However, restoration of the balance in a knee which is malaligned, especially if important structures such as the medial collateral ligament and the iliotibial tract are destroyed, may be unsatisfactory. It is also important to remember that the anatomical relationship of the components may change after soft tissue release. This is especially true of rotational alignment and therefore it is wise not to finalise the rotational...
should be on the lateral side. For valgus deformities the releases involves the cutting of normal tissue and then the insertion of the component and/or performing soft-tissue release. It is not clear to what extent such techniques should be used. Severe extra-articular deformities should probably be corrected at the site of the deformity in order not to compromise the TKR.

The interaction of alignment and prosthetic design

The technical goals of TKR need to be viewed in the context of the design of the implant. While most current designs share a fundamentally common approach, there are variations which need to be accommodated intellectually and in the surgical technique used. The most important design variable is the degree of inbuilt restraint in order to produce extra stability and thus prevent subluxation or dislocation. However, the restraining interface is almost invariably polyethylene, which will be exposed to high forces that can cause it to fail. These implants vary from the heavily-restrained hinge designs with only one degree of freedom to the posterior stabilised and deep-dished variants. Mobile-bearing designs aim to reduce restraint in rotation and therefore produce less wear of polyethylene and delay loosening. At present it is unclear how critical prosthetic alignment is in these variants or whether different designs require adjustment of the alignment of components.

The relationship between femorotibial and patellofemoral articulations

The positioning of the femorotibial articulation in relation to the patellofemoral has three determining parameters; the rotary (axial) position of the femorotibial complex, the relative balance of the actions of muscles and the tightness of ligaments acting across the patella and the position of the joint line. This defines the relative positions of the joint line and the patella. The position of the joint line is virtually uncontrolled in TKR.

The relationship between technical success and outcome

The impact of coronal alignment has been frequently described. To date, controlled studies have failed to show that an improvement in the coronal alignment of the components is associated with any short-term clinical benefit. However, most of the studies quoted have been seriously underpowered.13,14 It is widely accepted that a deviation of 3° from the neutral is associated with reduced longevity of the implant. However, there is very little direct evidence to support this view. It was first reported in 1991 in the context of a very unusual knee design, but has been supported by finite model analysis,15 in laboratory studies using a knee simulator,16 in cadaver studies17,18 and in a limited number of outcome studies.19 However, 3° is an arbitrary figure and there is no reason to believe that it represents a definitive value for the acceptability of alignment. It is more likely that any deviation from neutral will reduce longevity by an amount which is proportional to the malalignment.

It is more difficult to achieve good sagittal than coronal alignment20,21 yet the impact of sagittal malalignment has been studied relatively little. However, sagittal instability does occur22 and has been associated with an excessive tibial slope.23 Since variations in tibial slope produce reciprocal alterations in the flexion and extension gaps, the position of the tibial component until all the soft tissue releases have been performed.

The interaction of intra- and extra-articular deformity

Established and advanced intra-articular deformities seem to predispose to secondary extra-articular deformities, although the extent and nature of the associations have not been fully elucidated. Correction of intra-articular deformity does not affect any extra-articular parameter, at least in the short term. When extra-articular deformity is a considerable contributor to overall malalignment it is possible to restore a neutral mechanical axis of the limb by intra-articular techniques. These involve altering the alignment of the component and/or performing soft-tissue release. It is not clear to what extent such techniques should be used. Severe extra-articular deformities should probably be corrected at the site of the deformity in order not to compromise the TKR.

The interaction of extra-articular deformity and soft-tissue imbalance

If there is considerable extra-articular deformity, correct placement of the components will result in soft-tissue imbalance. This is most obvious in the coronal plane (Fig. 1). If the extra-articular deformity is varus, placement of the femoral component along the mechanical axis of the femur and of the tibial component along the mechanical axis of the tibia will result in a mechanical axis of the limb which passes medially to the joint and produces a relative lateral laxity. Theoretically, this can be corrected by performing a medial release, the extent of which is proportional to the extent of the initial extra-articular deformity. The release involves the cutting of normal tissue and then the insertion of a thick tibial plateau. For valgus deformities the releases should be on the lateral side.

Table II Mean (SD) angular deviations of 23 failed total knee replacements in degrees, expressed in absolute terms, from the ideal values

<table>
<thead>
<tr>
<th>Parameter*</th>
<th>Early failure &lt; 10 years (n = 16)</th>
<th>Late failure ≥ 10 years (n = 7)</th>
<th>p-value†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Femoral coronal</td>
<td>2.81 (1.56)</td>
<td>1.29 (1.38)</td>
<td>0.0367</td>
</tr>
<tr>
<td>Femoral sagittal</td>
<td>2.06 (1.84)</td>
<td>1.57 (1.81)</td>
<td>0.5610</td>
</tr>
<tr>
<td>Femoral axial</td>
<td>1.88 (1.86)</td>
<td>1.86 (2.04)</td>
<td>0.9837</td>
</tr>
<tr>
<td>Tibial coronal</td>
<td>1.75 (1.48)</td>
<td>1.14 (1.35)</td>
<td>0.3644</td>
</tr>
<tr>
<td>Tibial sagittal</td>
<td>2.94 (2.43)</td>
<td>2.57 (1.81)</td>
<td>0.7200</td>
</tr>
<tr>
<td>Femorotibial mismatch</td>
<td>6.38 (5.30)</td>
<td>1.14 (1.21)</td>
<td>0.0017</td>
</tr>
</tbody>
</table>

* for tibial sagittal the ideal is taken as the manufacturer’s recommended value for that particular prosthesis. For all other parameters the ideal value is taken as zero. The reference axes are mechanical axis of the femur for femoral coronal and femoral, sagittal, transepicondylar axis of the femur for femoral axial, and mechanical axis of the tibia for tibial coronal.

† Students’ t-test
complications of sagittal malalignment are probably the consequences of flexion-extension mismatch.

Rotary alignment
Excessive internal rotation of the femoral component is associated with undue lateral laxity in flexion and clinically gives rise to femorotibial instability, while excessive internal rotation of the tibiofemoral joint is associated with patellar maltracking and patellofemoral complications including subluxation and dislocation.

It is the practice in my unit for TKRs which come to revision to have the alignment of the failed components determined using the Perth CT Protocol. It has been shown that when the failures were subdivided into premature, with mechanical failure in less than ten years, and expected, with mechanical failure after ten years or more, there were only two alignment parameters which differed significantly in the two groups, the most marked being mismatch of the femoral and tibial components in rotation (Table II).

Soft-tissue balance
Re-tensioning of soft tissues which occurs during TKR improves proprioception. It is generally considered that knees which are unduly lax in any one direction fare badly. Instability is thought to be a result of combined errors in alignment and soft-tissue balance. Flexion instability is sometimes blamed on unequal gaps in flexion and extension, but no controlled studies have confirmed this. There is little evidence to show that there is a quantitative relationship between soft-tissue balance and outcome, partly because evaluation of ‘balance’ is totally subjective.

Joint line
As the joint line is moved distally relative to the patella, producing a patella alta, the patellofemoral contact forces increase by 3% per millimetre of displacement. Patella infera, a raised joint line, is a cause of a reduced range of movement. Errors in location of the joint line increase with each revision. However, control of the position of the joint line is difficult since the only useful reference is the transepicondylar axis of the femur. It is difficult to translate this into guidance at surgery, without computer assistance. The relationship between the level of the joint line, patellofemoral pain and the range of movement requires further investigation.

Summary
It is clear that there are substantial and important gaps in our knowledge of alignment of a TKR. Alignment can be regarded as significant for both the initial function and the longevity of the prosthesis. Alignment and soft-tissue balance are inextricably linked and in the absence of injury may be different manifestations of the same reality. The concept of soft-tissue balance will not become clearer until ligament balance is expressed quantitatively and longitudinal outcome studies have been undertaken. It is not known how sensitive patients are to malalignment, and how much effort is needed to achieve perfect alignment.

Alignment is a multidimensional concept and it is appropriate to consider only the mechanical axis of the limb. The sagittal and axial alignment of the components will probably prove to be as, or more, important in achieving a satisfactory TKR. In the design and assessment of studies quoted, alignments need to be considered in relation to the reference axes used and the studies should be judged by the validity of these axes. At present, it appears that the mechanical axes should be preferred to the others.

In the early post-operative phase the primary manifestation of malalignment is instability. More subtle variations in outcome, such as pain, range of movement and overall function will require very large series to detect differences because so many other factors affect these parameters. The relationship between the longevity of the components and alignment will require studies which measure alignment in all its variables soon after the initial surgery and then give a follow-up of ten to 15 years.

No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

References