

The relevance of ligament balancing in total knee arthroplasty: how important is it? A systematic review of the literature

Sina Babazadeh,^{1,2} James D. Stoney,¹
Keith Lim,³ Peter F.M. Choong^{1,2}

¹Department of Orthopaedics, St. Vincent's Hospital; ²University of Melbourne, Department of Surgery; ³Department of Rheumatology, St. Vincent's Hospital, Melbourne, Australia

Abstract

Ligament balancing affects many of the postoperative criteria for a successful knee replacement. A balanced knee contributes to improved alignment and stability. Ligament balancing helps reduce wear and loosening of the joint. A patient with a balanced knee is more likely to have increased range of motion and proprioception, and decreased pain. All these factors help minimize the need for revision surgery. Complications associated with ligament balancing can include instability caused by over-balancing and the possibility of neurovascular damage during or as a result of ligament balancing. This article attempts to summarize the literature, to define a balanced knee, and outline the benefits and possible complications of ligament balancing. Different techniques, sequences, and tools used in ligament balancing, and their relevance in correcting various deformities are reviewed.

Introduction

Nine percent of all knee replacements performed are for a revision.¹ Over the last decade the revision burden has been relatively constant.² Unless a limiting mechanism can be implemented, the number of revisions is likely to rise with the increasing number of arthroplasties performed.² This is projected to be a six-fold increase over the next 25 years.³ Nearly half of all knee revisions can be attributed to a cause that may be prevented with correct ligament balancing.^{1,4} There are large financial and medical costs associated with revision surgery.⁵ This and the poor outcomes in terms of function and pain relief⁶ underline the importance of efforts to minimize failure of knee replacements.

Definition of ligament balancing

Correct ligament balancing results in a "balanced knee." A balanced knee comprises the following characteristics:⁷⁻¹¹

- A full range of movement.
- Symmetrical medial-lateral balance at full extension and 90 degrees of flexion resulting in a rectangular tibiofemoral gap.
- Correct valgus/varus alignment in both flexion and extension.
- Balanced flexion-extension gap without medial-lateral tightness or laxity.
- A well-tracking patella during full motion.
- Maximal flexion occurring with the patella reduced and without excessive rollback of the femur on the tibia.
- Correct rotational balance between the tibial and femoral components.

Purpose of ligament balancing

The arthritic process leading to a total knee replacement causes joint deformity and osteophytes. This joint deformity can cause both irreversible ligament shortening on the collapsed side and elongated ligaments on the convex side. Osteophytes can cause tightness by tenting the ligaments resulting in restriction of movement and flexion contractures.¹² Ligament balancing attempts to counter these changes. This is achieved usually by removing osteophytes and lengthening and dissecting tight ligaments in sequence. Tightening lax ligaments, albeit more difficult and rarely used, also can play a role.^{13,14}

Advantages of ligament balancing

A balanced knee has many postoperative advantages, and this is supported by the literature,^{12,15-17} although randomized control studies of ligament balancing are limited.

Alignment

Ligament balancing has been shown to be important in producing better limb alignment.¹⁵ A series of normally aligned knees that went on to develop early medial insert wear progressing to varus malalignment pointed toward inadequate medial compartment ligament balancing as a possible cause.¹⁸ In addition, not fully balancing a valgus knee can result in the medial collateral ligaments remaining lax. As these do not tighten over time, the knee can revert to a valgus deformity.¹⁹ Patellofemoral joint mechanics also rely on correct alignment.¹⁸ Malalignment may result in lateral tracking and tilting of the patella and, rarely, patellar dislocation if severe.²⁰ Correct alignment can help prevent component loosening,²¹ improve tibiofemoral kinematics,²² and decrease shear forces.²³ Ligament balancing leading to correct alignment can prevent late instability²⁴ and prosthetic failure.¹⁵

Correspondence: Peter Choong, Department of Orthopaedics, Level 3 Daly Wing, 41 Victoria Parade, Fitzroy, VIC 3065, Australia.
E-mail: sarcoma@bigpond.net.au

Key words: ligament balancing, knee, arthroplasty.

Contributions: SB, main author and researcher; PC, JS, KL, substantial contributions to conception, design and editing of the article.

Conflict of interests: the authors report no conflicts of interest.

Received for publication: 1 August 2009.
Accepted for publication: 20 October 2009.

This work is licensed under a Creative Commons Attribution 3.0 License (by-nc 3.0).

©Copyright S. Babazadeh et al., 2009
Orthopedic Reviews 2009; 1:e26
doi:10.4081/or.2009.e26

Stability

Ligament balancing is a recognized key determinant of postoperative stability,²⁴⁻²⁶ and has been described as a possible preventable cause of the 27% of early knee revisions owing to instability.²⁷ Instability and malalignment at the time of the operation are recognized as preventable causes for a revision.^{27,28} Ligament incompetence can cause both early and late instability if not accounted for by using an appropriate prosthesis.²⁴ The role of ligament balancing in stability is even more pertinent with cruciate retaining prostheses. In such knees, an excessive flexion gap and late failure of the posterior cruciate ligament (PCL) is an often unrecognized cause of flexion instability.²⁹ With posterior stabilizing knee prostheses, a lax collateral ligament can cause a loose and asymmetrical flexion gap leading to flexion instability. Recurrent dislocations can occur as a result.¹⁹ An aggressive ligament release has been noted to be a risk factor for instability; but fear of creating instability leading to under-correction of a fixed angular deformity can cause an asymmetrical extension instability.¹⁹

Prosthetic wear

Prosthetic wear and ligament balancing are linked intrinsically. In one study looking at polyethylene wear at revision, 12 of 14 knees with asymmetrical wear lacked ligament release during the index case.³⁰ Ligament imbalance leading to malalignment is a likely risk factor for increased wear.^{16,18,31,32} Abnormal wear can be attributed to a tight PCL leading to increased loading.¹⁸ Wear can lead to osteolysis and prosthesis loosening owing to the production of debris,³³ and was noted as the third most common cause for a revision (Table 1).¹

Table 1. Diagnosis resulting in revision.¹

Reason for revision	Percentage of all revision cases (%)
Loosening	36.5
Infection	14.9
Tibial wear	7.5
Pain	7.2
Lysis	6.9
Patellofemoral pain	5.6
Tibial implant breakage	3.3
Progression of disease	3.1
Instability	2.9
Fracture	2.1
Arthrofibrosis	1.7

Prosthetic loosening

Balanced knees have a lower rate of prosthetic loosening.³⁰ Loosening is the most common cause for a revision (36.5%).¹ Radiolucent lines found on X-ray are likely to be a result of micromotion and are decreased with correct balancing.³⁴ This micromotion can increase osteoclast activity leading to osteolysis,³³ which can cause prosthetic loosening and failure. In addition, prosthetic wear can result in debris leading to osteolysis.³⁵

Pain and proprioception

One of the key goals of arthroplasty is to alleviate pain, and ligament balancing can help to achieve this goal. Pain can be associated with over-tight ligaments,³⁶ and instability is a significant cause of pain, which may be prevented with appropriate ligament balancing.²⁵ Proprioception was noted to be improved with correct balancing. In a study of 38 patients, significant improvement in proprioception was found in correctly balanced knees (defined as less than two degrees of varus/valgus alignment) at six months.³⁷

Ligament balancing can contribute to functional improvement. Unitt *et al.* looked at 526 knees one year postoperatively, and found that the Mean Clinical Rating Knee Score was significantly better with a balanced knee compared to an unbalanced knee.¹⁷ However, a significant difference in the Oxford Knee Score and Clinical Rating Functional Score was not shown to be associated with balancing.¹⁷ Range of motion (ROM) is an important predictor of functional outcome as it plays a role in performing activities of daily living; for example, squatting or sitting.³⁸ Unitt *et al.* reported that ROM was significantly better in knees balanced in flexion, especially in those knees that were unbalanced preoperatively. However, a significant change in ROM was not associated

Table 2. The valgus knee.

Valgus knee ligament balancing sequences					
	Whiteside ¹²		Favorito <i>et al.</i> ¹⁴	Clarke <i>et al.</i> ⁵⁵	Lombardi <i>et al.</i> ⁵⁷
Tight in flexion	Tight in extension	Tight in both		Pie-crusting technique	
Popliteal tendon.	Iliotibial band.	Popliteus tendon.	Tightest structure first	Posterolateral capsule.	Iliotibial band.
LCL.	Posterolateral capsule.	LCL.	(usually the LCL, sometimes iliotibial band).	Horizontal stab incisions laterally: usually beginning at iliotibial band	Posterolateral capsule.
Posterolateral capsule.		Posterolateral capsule.	Popliteal tendon.	then other tight structures.	Popliteal tendon.
		Balance in flexion. If still tight in extension then release iliotibial band.	Posterolateral capsule.		LCL.
			Gastrocnemius muscle.		
			Iliotibial band.		
			Reconstruct MCL.		

LCL, lateral collateral ligament; MCL, medial collateral ligament.

Table 3. The varus knee.

Tight in flexion	Varus knee ligament balancing sequences			Burke ⁷
	Whiteside ¹²	Insall ¹⁶		
	Tight in extension	Tight in both		
Anterior portion of MCL.	Posterior portion of MCL.	Anterior portion of MCL.	Semimembranosus tendon.	Deep MCL.
	Medial posterior capsule.	Posterior portion of MCL.	MCL.	Superficial MCL.
		Medial posterior capsule.		Pes anserina.
				Posterior capsule.
				Medial gastrocnemius muscle.

MCL, medial collateral ligament.

with the amount of extension balance achieved.¹⁷ Matsuda *et al.*'s review of 80 knees verified the significant improvement in ROM in balanced knees, and also reported a significant decrease in ROM with unbalanced knees.³⁹

Complications

Complications associated with ligament balancing are few. One article suggested an increased risk of postoperative hematoma, wound complications, and infection with ligament balancing.⁴⁰ Other studies have refuted these suggestions, stating no association could be identified between these complications and the extent of ligament balancing.¹⁷ Another serious complication is peroneal nerve (Figure 1) injury. The possible mechanisms of injury can be associated with ligament balancing, either through iatrogenic dis-

**Figure 1. Common peroneal nerve.**

section during balancing or stretching of the nerve when a severely valgus knee is realigned.¹⁴ In one series of 10361 consecutive knee replacements, 10 of the 32 cases of peroneal nerve palsy had a valgus deformity greater than 12 degrees preoperatively.⁴¹ Damage to other neurovascular structures, for example, the popliteal artery and vein, and tibial nerve, also can occur occasionally during posterior capsular release.⁴² Other factors to consider include the difficulty and technical demand of ligament balancing^{43,44} and the risk of excessive release leading to instability.¹⁷ In addition, surgeons should be aware that optimizing tibiofemoral balance occasionally can affect patellofemoral balance.^{45,46}

Overall, the literature indicates that ligament balancing has many advantages and plays a significant role in determining the success of total knee arthroplasty.^{15,16,34,47}

Techniques of ligament balancing

Two popular knee replacement techniques currently practiced are “measured resection” and “balanced resection.” Both incorporate ligament balancing during the operation, but with differing emphasis. In both techniques osteophytes are removed as the initial stage of achieving a balanced knee.

The “measured resection” technique involves performing the bone cuts and trialing the prosthesis before ligament balancing is undertaken (Figure 2). The basic principle is to resect a measured amount of bone from both the distal femur and proximal tibia. This amount should correspond to the thickness of the prosthesis. It relies on anatomical landmarks to determine the placement of the prosthetic components. Femoral and tibial preparations usually are performed independently using measured resection.⁴⁸ Once the bony cuts have been made trial prostheses are inserted. Then the knee is tested in flexion and extension when ligaments are released to correct gap asymmetry and ligament tightness.

The “balanced resection” technique differs in that the tibial bone cut is made first. Following this, symmetrical tension is applied to the joint line in extension using a ligament tensor, knee balancer, or laminar spreaders (Figure 3). This symmetrical tensioning demonstrates any varus/valgus deformity, which can be corrected using ligament balancing. Then the knee is placed in 90° flexion and the same tensioning device is used to distract the joint. The femoral component rotation is set by tension on the balanced ligaments and not by the anatomical landmarks.^{10,49,50}

All techniques attempt to correct leg alignment initially. Usually this is achieved successfully (within three degrees of the neutral) in

61-88% of knees.⁵¹ Following this, a rectangular and equal gap in flexion and extension is sought (ideally a <1 mm gap difference). A rectangular gap is achieved in most cases (84-90%). Achieving equal flexion and extension gaps is more difficult, with only a 50% success rate.^{44,51,52}

Alignment

The valgus knee

A valgus deformity has two defining factors: an element of bone loss and remodeling in the lateral compartment and soft-tissue contractures encompassing tight lateral structures (Figure 4). These contractures affect the lateral collateral ligament (LCL), iliotibial band, popliteus tendon, and posterolateral capsule (Figure 5).⁵³ This tight lateral aspect reflects the steps required to balance the deformity. Multiple techniques to balance the valgus knee have been described in the literature (Table 2). All start with the removal of osteophytes before attention is drawn to the ligaments. Early attempts at ligament balancing resulted in an unsatisfactory number of dislocations with a posteriorly stabilized prosthesis. This was likely to have been a result of over-release of the lateral ligaments and led to more detailed research to determine the best sequence of ligament release.⁵⁴

Whiteside¹² looked at the ligaments of the valgus knee and noted that the LCL, popliteus tendon, and posterolateral corner of the fibrous capsule have an effect on both flexion and extension. In extension, the LCL and posterolateral corner are more effective while in

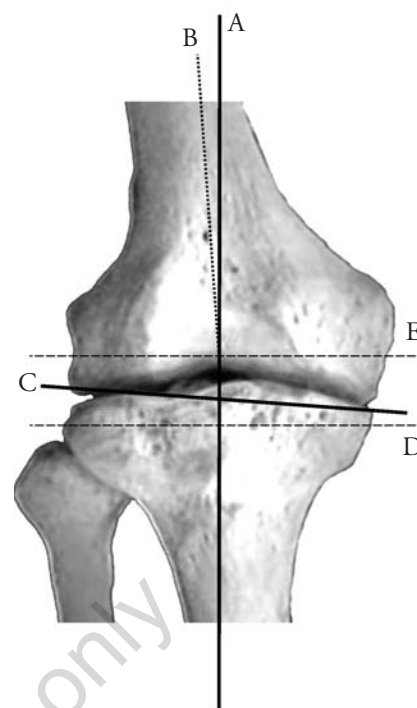


Figure 2. (A) Mechanical alignment, (B) anatomical alignment, (C) tibiofemoral angle, and (D, E) bony cuts.

flexion it is the popliteus tendon. With a valgus knee tight in both flexion and extension, he recommended initially balancing in flexion. The popliteus tendon should be released first, followed by the LCL, and finally the posterolat-

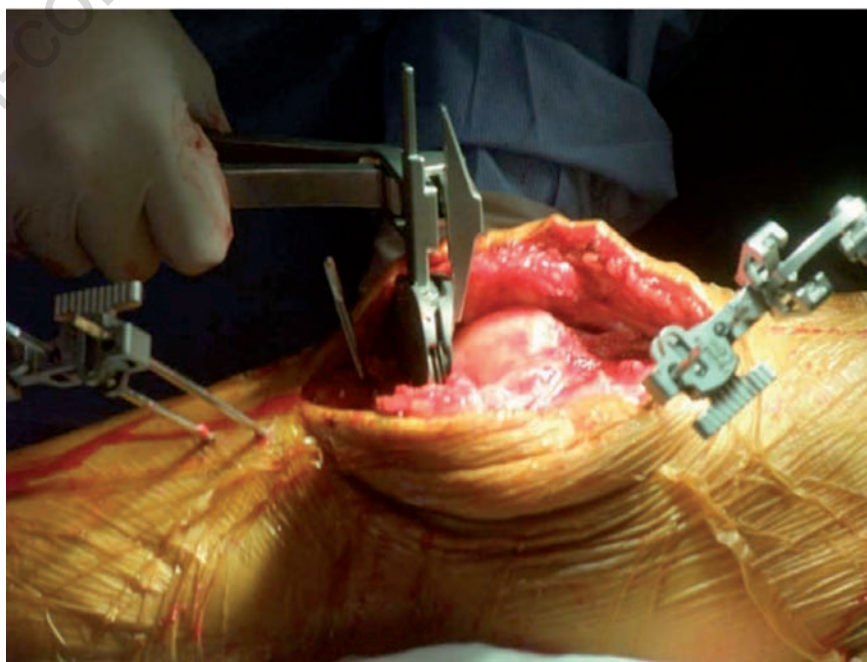


Figure 3. Balanced resection using tensor balancer device.

eral corner of the capsule. If the knee remains tight in extension, the iliotibial band should be released; a thicker spacer then can accommodate medial ligament laxity. In a valgus knee that is tight in extension only, Whiteside recommended the release of the iliotibial band. Occasionally the posterolateral capsule also needs to be released to achieve balance. If the knee is tight in flexion only, the recommendation is to release the popliteus tendon first. This is followed by the LCL and the posterolateral capsule, if necessary.¹²

Favorito *et al.*¹⁴ recommended the release of the tightest lateral structure first, usually the LCL. Then the surgeon should progressively release the popliteal tendon, posterolateral capsule, and the gastrocnemius muscle at its femoral origin, as needed. If the knee remains tight and the iliotibial band has not been resected, its resection is recommended at this stage. The LCL and popliteal tendon may be tied together using a locking-loop ligament suture to aid with support in flexion. If further balancing is required, the medial aspect should be reconstructed or a more constrained prosthesis used.¹⁴

The “pie-crust” technique is another method of ligament balancing for valgus deformities of less than 20 degrees.⁵⁵ The pie-crusting refers to a series of horizontal stab incisions, <5 mm in depth to avoid the peroneal nerve (Figure 1),^{52,56} along the lateral side through any structures that feel tight. This method is non-specific as to which structures are pie-crust, and no structure is completely resected. A laminar spreader works to stretch the lateral side progressively while the technique is being undertaken.

Another technique promoted by Lombardi *et al.*⁵⁷ begins with the release of the iliotibial band, followed by the release of the posterolateral capsule/arcuate complex from the distal part of the femur. Still unbalanced knees warrant the subsequent release of the popliteal tendon, followed by the gradual release of the collateral ligament from the distal part of the femur. These lateral soft-tissue stabilizers should retain partial attachment if possible to avoid the need for constrained devices. Lateral retinacular release may be needed to ensure correct patellofemoral tracking. The above sequence resulted in an average alignment of 5.8 degrees valgus, a Knee Society score of 88.9, and 94% prostheses survival rate in 97 consecutive cases with a minimum of two years’ follow-up.⁵⁷

The “inside-out” method reported by Ranawat *et al.*⁵⁸ for moderate to severe valgus deformities is similar to the above-mentioned technique but advocates the release of the PCL and the use of electrocautery for the intra-articular release of the posterolateral capsule. Forty-two knees with preoperative valgus deviation of more than 10 degrees that underwent



Figure 4. Severely valgus knee.



Figure 5. Posterior capsule.

balancing via the inside-out method were followed up by Elkus⁵⁶ over five years, with none having late instability, three needing revisions (owing to infection, polyethylene exchange, and patellar loosening, respectively), and with the mean Knee Society score being 93.

A cruciform lateral release has been described for severely valgus knees of more than 15 degrees. This method resulted in the postoperative valgus deformity decreasing from an average of 17 degrees to an acceptable 4.8 degrees with stability maintained during a two-year follow-up of the reported 35 cases.⁵⁹ In this technique a laminar spreader is inserted and the femoral component rotated via referencing to Whiteside’s line and/or the transepicondylar axis to achieve flexion gap symmetry. Tibial bony cuts are made, followed by balancing in extension. With the severely valgus knee, a lateral release will likely be needed to achieve extension gap symmetry and help correct patellar subluxation.⁶⁰ The cruciform lateral release begins with incising the lateral synovial layer to find the fatty layer containing the lateral superior geniculate vessels. The term “cruciform” refers to the next step involving two perpendicular cuts. The first is a vertical slit in the retinaculum just below the vessels, extended distally to the level of the tibial bone resection; the second cut begins at the level of the joint line and is extended 1-2 cm anteriorly and posteriorly, the anterior cut short of the patellar tendon and the posterior cut short of the lateral collateral ligament. Then trial components are inserted and further ligament balancing carried out, as necessary.⁵⁹

The varus knee

The varus knee usually is the simpler deformity to correct, although at its extreme it can



Figure 6. Varus knee.

be a daunting challenge (Table 3; Figure 6). For the minimally varus knee, Insall¹⁶ suggested that removal of the osteophytes may be sufficient to balance the knee. The next step should include the release of the semimembranosus tendon in a knee that is tight in extension, with tighter knees requiring a subperiosteal release of the medial collateral ligament (MCL).¹⁶ Burke⁷ advocated beginning with the release of the deep MCL subperiosteally, then moving to the superficial MCL. If the knee still is not balanced, consideration of the release of the pes anserina, posterior capsule, and the origin of the medial gastrocnemius muscle should be made, in that order.⁷

In a varus knee tight in flexion, Whiteside¹² noted that the medial femoral condyle tends to sit further posteriorly than the lateral condyle. The tibia can pivot around the MCL in such cases. To balance these knees he recommended the release of the anterior portion of the MCL with the knee flexed. When the knee is tight in extension only, he recommended the release of the posterior portion of the MCL. The medial posterior capsule can be released if the knee remains unbalanced. With a knee that is tight in both flexion and extension, the surgeon should begin with the release of the anterior portion of the MCL. Often the posterior portion needs to be released as well to gain balance. Occasionally the knee still does not extend fully. In such cases the posterior capsule may need to be released.¹²

Flexion contractures

The basic algorithm for correcting flexion contractures in one study begins with medial-lateral ligament balancing with resection of osteophytes and over-resection of the distal femur by 2 mm. This is followed by progressive posterior capsular release and gastrocnemius release.⁶¹ Sectioning of the posterior capsule has the possible complication of damaging the neurovascular bundle and hence must be performed with great care.⁶² If required, further resection of the distal femur and hamstring tenotomy may help.^{63,64} In 98.6% of cases of contractures of less than 30 degrees, only the first three steps were required to correct the contracture.^{64,65}

One must be wary not to increase the distal femoral bone resection before the knee is balanced. It can alter the joint line and slacken the quadriceps muscles in extension. Likewise it can decrease the height of the posterior femoral condyles available for fixation to the posterior aspect of the femoral component.⁶⁵ Increasing the tibial slope inadvertently can worsen a flexion contracture by building up the anterior portion of the tibial component, leading to anterior impingement. Other factors that may cause a flexion contracture include component malpositioning, insufficient bony cuts, using pillows to bolster the knees postop-

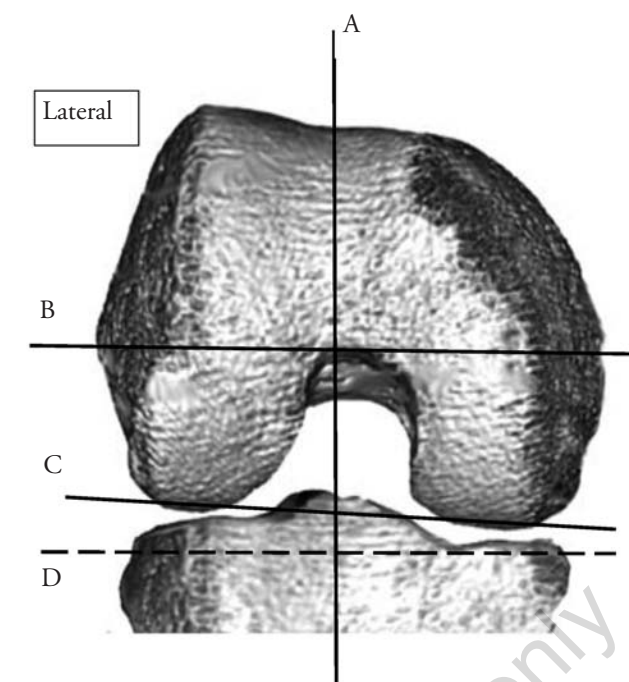


Figure 7. (A) Whiteside's line, (B) epicondylar axis, (C) posterior condylar axis, and (D) tibial bony cut, perpendicular to tibial long axis.

eratively, and the non-stop use of a continuous passive motion device.⁶²

Femoral rotation

To achieve the required rectangular flexion gap, femoral rotation must be considered when balancing the knee. Incorrect femoral rotations can result in a trapezoidal flexion gap, which can lead to patellofemoral tracking problems,^{14,66} instability, dysfunctional overall biomechanics,^{20,23,67-69} and anterior knee pain.⁵² To achieve correct femoral rotation, two methods have been devised.⁶⁶ The first relies on the tibial cut being performed prior to the femoral cut. This method, termed the "classic method," relies on a tensed knee in flexion post-ligament balancing in extension, followed by an anteroposterior (AP) cut of the femur parallel to the cut surface of the tibia.^{16,70} This method is especially useful for more severely malaligned knees as it adjusts for changes in laxity that occur post-ligament balancing and compensates for unexpected bone loss.⁶⁶ In a number of studies it has been shown to be a highly accurate method of determining rotation and producing a rectangular flexion-extension gap.^{52,71}

The second method relies on osseous landmarks (Figure 7). This method has become popular as the majority of implant manufacturers base their AP cuts on these landmarks.⁶⁶ Three separate bony landmarks have been identified to aid with defining rotation. These include:

- The posterior condylar axis, using a neutral or three degrees of external rotation cut (Figure 7, line C).⁷²
- The epicondylar axis, using a parallel cut

(Figure 7, line B).⁷³

- Whiteside's line or the transverse axis of the femoral component, with the cut being made perpendicular to the line passing through the trochlear groove from the lateral edge of the PCL (Figure 7, line A).^{12,74}

The posterior condylar system generally has been shown to be the least accurate landmark for determining rotation.^{52,75} This is true for valgus or rheumatoid knees,^{7,52} especially when unexpected posterior bone-loss is present,⁶⁶ and also in varus knees as varus obliquity of the proximal tibia is associated with a higher posterior condylar angle.⁵² Consequently there is a trend away from using this landmark.⁵² When able to be palpated correctly the epicondylar axis is an accurate way of determining rotation.^{7,52} Using this landmark allows the knee's natural biomechanics to occur^{22,76,77} with excellent patellofemoral tracking and minimized tibiofemoral instability, reducing wear.⁷⁸ Lateral retinacular release for femoral component rotation is less likely when the epicondylar axis is used compared to using the posterior condylar landmark.⁵⁶ However, with a deficient lateral condyle, this landmark becomes inaccurate, resulting in false external rotation.⁷ Using Whiteside's line to determine rotation has been deemed accurate.⁷⁴ Its use is associated with significant reduction in patellofemoral problems when compared to the posterior condylar system. Systems using Whiteside's line or the epicondylar axis compensate well for posterior condylar bone loss but still are unable to take into account the change in knee laxity after complete ligamentous balancing in extension. This can result in rotation errors of at least three degrees.⁶⁶

Marked anterior osteophytes in the intra-trochlear groove may decrease the accuracy of systems using Whiteside's line significantly.⁷ In a review of 107 knees operated on using Whiteside's line, only one was reported as suffering patellar malalignment needing intervention.⁷⁴ The overall consensus suggests that using any single landmark can be inaccurate and that the use of multiple landmarks, erring on external rotation, produces the best results.^{7,79}

Flexion-extension gap

The basis of flexion-extension gap balancing is an attempt to obtain equal sized, rectangular gaps in both flexion and extension.^{11,80} Both the flexion and extension gap should be equal as the femoral prosthesis has a uniform thickness in flexion and extension. An unequal flexion-extension gap can result in overstuffing of the joint where the gap is smallest and/or laxity of the knee where the gap is largest.⁶² In addition, the gap should be rectangular in both flexion and extension. This has been demonstrated to have superior results compared to a trapezoidal flexion gap. In a randomized control study of 188 knees at three years' post-surgery, the rectangular gap cohort, when compared to the trapezoidal flexion gap control, was found to have an increased range of flexion (112 vs. 100 degrees, $p < 0.01$), decreased incidence of medial tibial pain (3% vs. 15%, $p < 0.001$), and decreased need for a lateral retinacular release (10% vs. 25%, $p < 0.05$).⁷²

Factors affecting the flexion-extension gap include tension of both the medial and lateral soft tissue structures, the PCL, position of the joint line, and size of the femoral component.¹¹ Balancing can be hard to achieve as the release of certain structures, like the MCL, can affect the gap differently in flexion and extension. Modifying the flexion gap can result in significant changes to the extension gap, most notably on the medial aspect.⁸⁴ In the anterior cruciate ligament (ACL)-resected normal knee, the joint gap can be altered significantly by different angles of flexion. Usually the gap is smaller at zero degrees flexion with the lateral joint gap increasing with flexion.⁸² As the joint gap is balanced in extension, the tension of the ligaments can change in flexion.⁸³ Hence, some surgeons advocate the use of ligament balancing to produce a rectangular extension gap and bony cuts to produce a rectangular flexion gap.

Ries *et al.* attempted to compose a simple set of rules to counter flexion-extension gap imbalance in revision arthroplasty.¹¹ The techniques mentioned can be helpful also for primary arthroplasty. Extension gap modification was found to be best achieved with distal augmentation of the femur and sizing of the femoral component for a loose extension gap

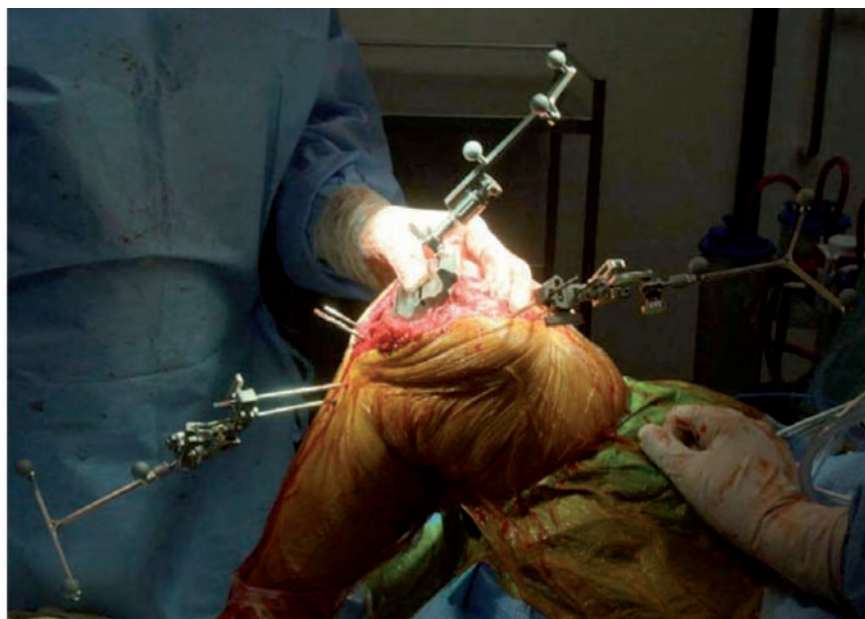


Figure 8. Computer-assisted surgery.

or continued resection of the femur for a tight extension gap. Flexion gap symmetry was achieved through anterior or posterior shifting of the femoral component or sizing changes of the anteroposterior dimension of the femoral component, using a larger component for a loose flexion gap and vice versa. The flexion and the extension gap is altered evenly by changing tibial component height, insert thickness,^{11,84} and via increased bone resection from the tibia.¹⁹ Changing the thickness is reported to have a significant influence on all laxity measurements,⁸⁵ and is a critical factor affecting knee tightness.⁹ The tibial slope can affect the flexion gap because the tibiofemoral contact point is more posterior in flexion than extension. Increasing the tibial slope will result in an increase in the flexion gap while only minimally affecting the extension gap.⁶² In addition, incorrect femoral component rotation may cause gap imbalance. Over-internally rotating the femoral component may cause medial flexion space tightness, while excessive external rotation can lead to lateral flexion space tightness.⁶² Apart from the aforementioned complications of an unbalanced knee, specific complications of an unstable flexion-extension gap include the indirect iatrogenic rupture of the PCL caused by the patient trying to overcome decreased flexion owing to an overly tight flexion space.¹⁹

The role of the posterior cruciate ligament

In total knee arthroplasty, the PCL is divided in 20% of cases, usually for correction of the

flexion gap.⁸⁶ Proper tensioning of this ligament is important if a cruciate-retaining prosthesis is to be used.⁸⁷ Reasons for retaining a PCL include preservation of bone stock, reduced risk of posterior dislocation, and no issues with peg wear.⁶² Reasons to resect the PCL revolve around possible increased flexion, increased flexion gap, and no risk of subsequent PCL failure resulting in instability. Previous studies suggesting improved kinematics with an intact PCL retaining femoral roll-back^{87,88} have been questioned in in vitro studies using MRI.⁸⁹ If the PCL is to be retained, balancing is essential, as excess laxity can result in anteroposterior instability. This is addressed rarely, leading to polyethylene wear and consequent failure. Conversely an excessively tight PCL will lead to pain and additional wear.⁹⁰ Stiffness (which is quantified by displacement versus load during ROM), also is found to be significantly increased in PCL-retaining knees.⁹¹

The fibers of the PCL run obliquely in the AP plane. The PCL is the main factor determining the contact point of the medial femoral condyle on the tibia from 60 to 120 degrees of flexion. Tensioning the PCL affects not only the flexion gap but also the anterior translation of the tibia compared to the femur. A 1:2 ratio exists between the increase in flexion gap and anterior translation of the tibia. This has significant implications on the contact point of the femur on the tibia. If the PCL is lax, the femur may slide forward on the tibia, and if the PCL is too tight the femur can sit posterior to the desired position. A well-balanced PCL can improve ROM.⁶²

The PCL is a secondary restraint to both varus and valgus stress. The PCL only begins to contribute to balancing the knee once either of the collateral ligaments has been released. In these instances the PCL plays a major role in valgus stability especially at the further ranges of flexion; that is, 60 to 90 degrees. It also contributes to rotational stabilization through the entire ROM. Its role in stabilizing a varus knee where the MCL has been sacrificed is crucial, to such an extent that over-release may require a highly constraint implant.¹⁰

The role of the PCL in flexure contractures of the knee has been controversial, with some authors advocating its release in this situation.⁶³ Later research disputes this and demonstrates that, to the contrary, the release of the PCL can make matters worse by creating an even larger mismatch between the extension and flexion space. This may cause the need for an increase in tibial thickness to counter the larger flexion gap, resulting in possible reduction in range of movement at extension.⁹² This leads to the main indication for PCL release: to increase flexion space.^{65,92} One study showed an increase of 4 mm in the flexion space, compared with the extension space, when the PCL was sacrificed.⁹² Its role governing the flexion space is more pertinent in a varus knee as the PCL tends to elongate and be less responsible for tightness in a valgus knee.⁶⁵

Tools

Computer-assisted surgery

Over the last few years there have been many technological advances in knee arthroplasty, most notably the introduction of computer-assisted surgery (CAS), which can help with both alignment and balancing (Figure 8). The benefits of CAS versus conventional knee arthroplasty have been studied extensively. Most agree that better alignment, that is less than three degrees of neutral, can be achieved with CAS.^{51,93,94} The relative risk of malalignment has been reported to decrease by 25%.⁹⁵ A recent meta-analysis of the current literature failed to verify improved long-term outcomes with CAS.⁹⁵ This was attributed to methodological weaknesses in the current literature preventing reliable inferences.⁹⁵ However, more current literature has criticized this meta-analysis for including non-randomized and cohort studies.⁵¹ A recent randomized control study of 111 patients suggested a significant difference in alignment as contributing to an improved functional outcome and quality of life with CAS.^{51,96} Improved alignment was associated with significantly better International Knee Scores ($p < 0.001$) and SF-12 scores ($p = 0.003$) at six months postoperatively.⁵¹ Others attest to no or minimal clinical benefit over conventional methods.^{95,97} In the subset of obese people, CAS may be more beneficial^{51,96}

as correct alignment seems to have a greater role in implant longevity in such cases.⁹⁸ The role of CAS with ligament balancing is limited. It has the ability to gauge alignment and flexion-extension gaps, but it is unable to advise the surgeon as to what soft tissue structures need to be amended to correct them.⁴⁹ Another study addressed the use of CAS in ligament balancing. It found that before the insertion of the components, CAS had a beneficial effect on balancing. After the components were in place, no difference in terms of knee load were found compared to traditional balancing techniques.⁹⁹ A clear role of CAS seems to be in surgical training. It improves surgical technique and alignment perception.⁹⁷

Joint distracters

Studies of the benefits of instrument joint distracters found no consistently significant difference in postoperative balance compared to traditional methods. However, the distracters did seem to result in slightly closer-to-normal knee kinematics with a medial pivot motion pattern during stair climbing.^{44,100} These devices now are replacing trial components as an option for ligament balancing more commonly.^{9,47,101}

Pressure sensing devices

The use of intraoperative pressure sensing devices to aid balancing has been evaluated. These accurately measure real-time tibiofemoral contact forces during range of motion.¹⁰² With the aid of such devices, it has been remarked that those knees with abnormal compartment pressure intraoperatively were more likely to have abnormal kinematics postoperatively. In comparison those knees with near-equal pressures rarely suffered from significant condylar lift-off postoperatively.¹⁸

Conclusion

The vast majority of articles in the literature supports the concept that a balanced knee is beneficial to the success of total knee arthroplasty. Its relevance is determined by its contribution to improving alignment and stability. A balanced knee is likely to have reduced wear and loosening. The patient with a balanced knee is likely to be more satisfied with an increased ROM and proprioception, and less pain. However, the surgeon must be wary of possible complications; for example, instability from excessive ligament resection and the possibility of peroneal nerve damage.

Currently no consensus exists regarding the best method to produce a balanced knee. Many differing techniques and sequences for ligament release have been reported over the many years since Freeman and Insall first

highlighted the importance of ligament balancing in the late seventies. New tools have been introduced to help the surgeon; for example, computer-assisted surgery and tensor balancers. However, randomized control trials comparing different techniques, sequences, and tools are limited. The best method of achieving the balanced knee is yet to be determined.

References

1. AOA national joint replacement registry. AOA, 2009 [cited 2009 17/02/2009]; <http://www.dmac.adelaide.edu.au/aoanjrr/index.jsp>.
2. Kurtz S, Mowat F, Ong K, et al. Prevalence of primary and revision total hip and knee arthroplasty in the United States from 1990 through 2002. *J Bone Joint Surg Am* 2005;87:1487-97.
3. Kurtz S, Ong K, Lau E, et al. Projections of primary and revision hip and knee arthroplasty in the United States from 2005 to 2030. *J Bone Joint Surg Am* 2007;89:780-5.
4. Sheng PY, Kontinen L, Lehto M, et al. Revision total knee arthroplasty: 1990 through 2002. A review of the Finnish arthroplasty registry. *J Bone Joint Surg Am* 2006;88:1425-30.
5. Bozic KJ, Durbhakula S, Berry DJ, et al. Differences in patient and procedure characteristics and hospital resource use in primary and revision total joint arthroplasty: a multicenter study. *J Arthroplasty* 2005; 20:S17-25.
6. Klenerman L. The evolution of orthopaedic surgery. London: Royal Society of Medicine Press; 2002.
7. Chapman MW. Chapman's orthopaedic surgery. 3rd edn. Philadelphia: Lippincott Williams & Wilkins, 2001.
8. Krackow KA. Revision total knee replacement ligament balancing for deformity. *Clin Orthop Relat Res* 2002;404:152-7.
9. D'Lima DD, Patil S, Steklov N, et al. An ABJS Best Paper: Dynamic intraoperative ligament balancing for total knee arthroplasty. *Clin Orthop Relat Res* 2007;463:208-12.
10. Whiteside LA, Saeki K, Mihalko WM. Functional medical ligament balancing in total knee arthroplasty. *Clin Orthop Relat Res* 2000;380:45-57.
11. Ries MD, Haas SB, Windsor RE. Soft-tissue balance in revision total knee arthroplasty. *J Bone Joint Surg Am* 2003;85-A:S38-42.
12. Whiteside LA. Ligament balancing in total knee arthroplasty: an instructional manual. New York: Springer, 2004.
13. Tria AJ Jr. Management of fixed deformi-

- ties in total knee arthroplasty. *J Long Term Eff Med Implants* 2004;14:33-50.
14. Favorito PJ, Mihalko WM, Krackow KA. Total knee arthroplasty in the valgus knee. *J Am Acad Orthop Surg* 2002;10:16-24.
 15. Sharkey PF, Hozack WJ, Rothman RH, et al. Insall Award paper. Why are total knee arthroplasties failing today? *Clin Orthop Relat Res* 2002;404:7-13.
 16. Insall JN. *Surgery of the knee*. New York: Churchill Livingstone, 1984.
 17. Unitt L, Sambatakakis A, Johnstone D, et al. Short-term outcome in total knee replacement after soft-tissue release and balancing. *J Bone Joint Surg Br* 2008; 90:159-65.
 18. Wasielewski RC, Galat DD, Komistek RD. Correlation of compartment pressure data from an intraoperative sensing device with postoperative fluoroscopic kinematic results in TKA patients. *J Biomech* 2005; 38:333-9.
 19. Parratte S, Pagnano MW. Instability after total knee arthroplasty. *J Bone Joint Surg Am* 2008;90:184-94.
 20. Berger RA, Crossett LS, Jacobs JJ, et al. Malrotation causing patellofemoral complications after total knee arthroplasty. *Clin Orthop Relat Res* 1998;356:144-53.
 21. Jeffery RS, Morris RW, Denham RA. Coronal alignment after total knee replacement. *J Bone Joint Surg Br* 1991; 73:709-14.
 22. Miller MC, Berger RA, Petrella AJ, et al. Optimizing femoral component rotation in total knee arthroplasty. *Clin Orthop Relat Res* 2001;392:38-45.
 23. Anouchi YS, Whiteside LA, Kaiser AD, et al. The effects of axial rotational alignment of the femoral component on knee stability and patellar tracking in total knee arthroplasty demonstrated on autopsy specimens. *Clin Orthop Relat Res* 1993; 287:170-7.
 24. Fehring TK, Valadie AL. Knee instability after total knee arthroplasty. *Clin Orthop Relat Res* 1994;299:157-62.
 25. Miyasaka KC, Ranawat CS, Mullaji A. 10- to 20-year followup of total knee arthroplasty for valgus deformities. *Clin Orthop Relat Res* 1997;345:29-37.
 26. Takahashi T, Wada Y, Yamamoto H. Soft-tissue balancing with pressure distribution during total knee arthroplasty. *J Bone Joint Surg Br* 1997;79:235-9.
 27. Fehring TK, Odum S, Griffin WL, et al. Early failures in total knee arthroplasty. *Clin Orthop Relat Res* 2001;392:315-8.
 28. Rand JA, Bryan RS. Revision after total knee arthroplasty. *Orthop Clin North Am* 1982;13:201-12.
 29. Pagnano MW, Hanssen AD, Lewallen DG, et al. Flexion instability after primary posterior cruciate retaining total knee arthroplasty. *Clin Orthop Relat Res* 1998;356:39-46.
 30. Wasielewski RC, Galante JO, Leighty RM, et al. Wear patterns on retrieved polyethylene tibial inserts and their relationship to technical considerations during total knee arthroplasty. *Clin Orthop Relat Res* 1994; 299:31-43.
 31. Yercan HS, Ait Si Selmi T, Sugun TS, et al. Tibiofemoral instability in primary total knee replacement: a review. Part I: Basic principles and classification. *Knee* 2005; 12:257-66.
 32. Vince KG, Abdeen A, Sugimori T. The unstable total knee arthroplasty: causes and cures. *J Arthroplasty* 2006;21:S44-9.
 33. Bartl R. Bisphosphonates in medical practice: actions, side effects, indications, strategies. New York: Springer, 2007.
 34. Sambatakakis A, Wilton TJ, Newton G. Radiographic sign of persistent soft tissue imbalance after knee replacement. *J Bone Joint Surg Br* 1991;73:751-6.
 35. Malek MM. *Knee surgery: complications, pitfalls, and salvage*. New York: Springer, 2001.
 36. Lombardi AV, editor. *Primary total knee arthroplasty: surgical techniques and principles*. Instructional course lecture. AAOS 73rd Annual Meeting, Chicago, IL, 2006.
 37. Attfield SF, Wilton TJ, Pratt DJ, et al. Soft-tissue balance and recovery of proprioception after total knee replacement. *J Bone Joint Surg Br* 1996;78:540-5.
 38. Kim JM, Moon MS. Squatting following total knee arthroplasty. *Clin Orthop Relat Res* 1995;313:177-86.
 39. Matsuda Y, Ishii Y, Noguchi H, et al. Varus-valgus balance and range of movement after total knee arthroplasty. *J Bone Joint Surg Br* 2005;87:804-8.
 40. Kumar PJ, Dorr LD. Severe malalignment and soft-tissue imbalance in total knee arthroplasty. *Am J Knee Surg* 1997;10:36-41.
 41. Idusuyi OB, Morrey BF. Peroneal nerve palsy after total knee arthroplasty. Assessment of predisposing and prognostic factors. *J Bone Joint Surg Am* 1996;78:177-84.
 42. Ayers DC, Dennis DA, Johanson NA, et al. AAOS Instructional course lectures: Common complications of total knee arthroplasty. *J Bone Joint Surg Am* 1997;79-A:278-311.
 43. Moreland JR. Mechanisms of failure in total knee arthroplasty. *Clin Orthop Relat Res* 1988;226:49-64.
 44. Griffin FM, Insall JN, Scuderi GR. Accuracy of soft tissue balancing in total knee arthroplasty. *J Arthroplasty* 2000;15:970-3.
 45. Stiehl JB, Cherveny PM. Femoral rotational alignment using the tibial shaft axis in total knee arthroplasty. *Clin Orthop Relat Res* 1996;331:47-55.
 46. Figgie HE 3rd, Goldberg VM, Heiple KG, et al. The influence of tibial-patellofemoral location on function of the knee in patients with the posterior stabilized condylar knee prosthesis. *J Bone Joint Surg Am* 1986;68:1035-40.
 47. Freeman MA, Todd RC, Bamert P, et al. ICLH arthroplasty of the knee: 1968-1977. *J Bone Joint Surg Br* 1978;60-B:339-44.
 48. Winemaker MJ. Perfect balance in total knee arthroplasty: the elusive compromise. *J Arthroplasty* 2002;17:2-10.
 49. Dennis DA, Fehring TK. P.F.C. Sigma RP knee system surgical technique. 1st edn. Warsaw: DePuy Orthopaedics, 2007.
 50. Insall J, Ranawat CS, Scott WN, et al. Total condylar knee replacement: preliminary report. *Clin Orthop Relat Res* 1976;120: 149-54.
 51. Choong PF, Dowsey MM, Stoney JD. Does accurate anatomical alignment result in better function and quality of life? A prospective randomized controlled trial comparing conventional and computer-assisted total knee arthroplasty. *J Arthroplasty* 2008;24:681-8.
 52. Archibeck MJ, White RE Jr. What's new in adult reconstructive knee surgery. *J Bone Joint Surg Am* 2001;83-A:1444-50.
 53. Ranawat CS. *Total-condylar knee arthroplasty: technique, results, and complications*. New York: Springer-Verlag, 1985.
 54. Mihalko WM, Krackow KA. Anatomic and biomechanical aspects of pie crusting posterolateral structures for valgus deformity correction in total knee arthroplasty: a cadaveric study. *J Arthroplasty* 2000;15: 347-53.
 55. Clarke HD, Fuchs R, Scuderi GR, et al. Clinical results in valgus total knee arthroplasty with the "pie crust" technique of lateral soft tissue releases. *J Arthroplasty* 2005;20:1010-4.
 56. Archibeck MJ, White RE Jr. What's new in adult reconstructive knee surgery. *J Bone Joint Surg Am* 2005;87:1656-66.
 57. Lombardi AV Jr, Dodds KL, Berend KR, et al. An algorithmic approach to total knee arthroplasty in the valgus knee. *J Bone Joint Surg Am* 2004;86-A:62-71.
 58. Ranawat AS, Ranawat CS, Elkus M, et al. Total knee arthroplasty for severe valgus deformity. *J Bone Joint Surg Am* 2005; 87:S271-84.
 59. Politi J, Scott R. Balancing severe valgus deformity in total knee arthroplasty using a lateral cruciform retinacular release. *J Arthroplasty* 2004;19:553-7.
 60. Stern SH, Moeckel BH, Insall JN. Total knee arthroplasty in valgus knees. *Clin Orthop Relat Res* 1991;273:5-8.
 61. Lombardi AV Jr, Mallory TH, Fada RA, et al. An algorithm for the posterior cruciate ligament in total knee arthroplasty. *Clin*

- Orthop Relat Res 2001;392:75-87.
62. Bellemans J, Ries MD, Victor J. Total knee arthroplasty: A guide to get better performance. Hidelberg: Springer, 2005.
63. Lu H, Mow CS, Lin J. Total knee arthroplasty in the presence of severe flexion contracture: a report of 37 cases. J Arthroplasty 1999;14:775-80.
64. Bellemans J, Vandenuecker H, Victor J, et al. Flexion contracture in total knee arthroplasty. Clin Orthop Relat Res 2006;452:78-82.
65. Mihalko WM, Whiteside LA. Bone resection and ligament treatment for flexion contracture in knee arthroplasty. Clin Orthop Relat Res 2003;406:141-7.
66. Fehring TK. Rotational malalignment of the femoral component in total knee arthroplasty. Clin Orthop Relat Res 2000;380:72-9.
67. Scuderi GR, Komistek RD, Dennis DA, et al. The impact of femoral component rotational alignment on condylar lift-off. Clin Orthop Relat Res 2003;410:148-54.
68. Barrack RL, Schrader T, Bertot AJ, et al. Component rotation and anterior knee pain after total knee arthroplasty. Clin Orthop Relat Res 2001;392:46-55.
69. Akagi M, Matsusue Y, Mata T, et al. Effect of rotational alignment on patellar tracking in total knee arthroplasty. Clin Orthop Relat Res 1999;366:155-63.
70. Scuderi GR, Insall JN. The posterior stabilized knee prosthesis. Orthop Clin North Am 1989;20:71-8.
71. Katz MA, Beck TD, Silber JS, et al. Determining femoral rotational alignment in total knee arthroplasty: reliability of techniques. J Arthroplasty 2001;16:301-5.
72. Laskin RS. Flexion space configuration in total knee arthroplasty. J Arthroplasty 1995;10:657-60.
73. Berger RA, Rubash HE, Seel MJ, et al. Determining the rotational alignment of the femoral component in total knee arthroplasty using the epicondylar axis. Clin Orthop Relat Res 1993;286:40-7.
74. Whiteside LA, Arima J. The anteroposterior axis for femoral rotational alignment in valgus total knee arthroplasty. Clin Orthop Relat Res 1995;321:168-72.
75. Griffin FM, Insall JN, Scuderi GR. The posterior condylar angle in osteoarthritic knees. J Arthroplasty 1998;13:812-5.
76. Olcott CW, Scott RD. The Ranawat Award. Femoral component rotation during total knee arthroplasty. Clin Orthop Relat Res 1999;367:39-42.
77. Insall JN, Scuderi GR, Komistek RD, et al. Correlation between condylar lift-off and femoral component alignment. Clin Orthop Relat Res 2002;403:143-52.
78. Archibeck MJ, White RE Jr. What's new in adult reconstructive knee surgery. J Bone Joint Surg Am 2002;84-A:1719-26.
79. Eckhoff DG, Bach JM, Spitzer VM, et al. Three-dimensional morphology and kinematics of the distal part of the femur viewed in virtual reality. Part II. J Bone Joint Surg Am 2003;85-A:S97-104.
80. Lombardi AV Jr, Berend KR, Leith JR, et al. Posteriorstabilized constrained total knee arthroplasty for complex primary cases. J Bone Joint Surg Am 2007;89:S90-102.
81. Sugama R, Kadota Y, Kobayashi A, et al. Preparation of the flexion gap affects the extension gap in total knee arthroplasty. J Arthroplasty 2005;20:602-7.
82. Tanaka K, Muratsu H, Mizuno K, et al. Soft tissue balance measurement in anterior cruciate ligament-resected knee joint: cadaveric study as a model for cruciate-retaining total knee arthroplasty. J Orthop Sci 2007;12:149-53.
83. Fehring TK. Ligamentous balancing in rotating-platform knees. Orthopedics 2006;29:S56-9.
84. Firestone TP, Eberle RW. Surgical management of symptomatic instability following failed primary total knee replacement. J Bone Joint Surg Am 2006;88:S80-4.
85. Archibeck MJ, White RE Jr. What's new in adult reconstructive knee surgery. J Bone Joint Surg Am 2006;88:1677-86.
86. Firestone TP, Krackow KA, Davis JD 4th, et al. The management of fixed flexion contractures during total knee arthroplasty. Clin Orthop Relat Res 1992;284:221-7.
87. Pagnano MW, Cushner FD, Scott WN. Role of the posterior cruciate ligament in total knee arthroplasty. J Am Acad Orthop Surg 1998;6:176-87.
88. Morberg P, Chapman-Sheath P, Morris P, et al. The function of the posterior cruciate ligament in an anteroposterior-gliding rotating platform total knee arthroplasty. J Arthroplasty 2002;17:484-9.
89. Freeman MA, Pinskerova V. The movement of the knee studied by magnetic resonance imaging. Clin Orthop Relat Res 2003;410:35-43.
90. Saleh KJ, Clark CR, Sharkey PF, et al. Modes of failure and preoperative evaluation. J Bone Joint Surg Am 2003;85-A:S21-5.
91. Palzal P, Papini M, Petruccioli D, et al. An in vivo biomechanical analysis of the soft-tissue envelope of osteoarthritic knees. J Arthroplasty 2004;19:217-23.
92. Mihalko WM, Krackow KA. Posterior cruciate ligament effects on the flexion space in total knee arthroplasty. Clin Orthop Relat Res 1999;360:243-50.
93. Dutton AQ, Yeo SJ, Yang KY, et al. Computer-assisted minimally invasive total knee arthroplasty compared with standard total knee arthroplasty. A prospective, randomized study. J Bone Joint Surg Am 2008;90:2-9.
94. Perlick L, Bathis H, Lerch K, et al. [Navigated implantation of total knee endoprostheses in secondary knee osteoarthritis of rheumatoid arthritis patients as compared to conventional technique]. Z Rheumatol 2004;63:140-6.
95. Bauwens K, Matthes G, Wich M, et al. Navigated total knee replacement. A meta-analysis. J Bone Joint Surg Am 2007;89:261-9.
96. Ek ET, Dowsey MM, Tse LF, et al. Comparison of functional and radiological outcomes after computer-assisted versus conventional total knee arthroplasty: a matched-control retrospective study. J Orthop Surg Hong Kong 2008;16:192-6.
97. Stulberg SD, Yaffe MA, Koo SS. Computer-assisted surgery versus manual total knee arthroplasty: a case-controlled study. J Bone Joint Surg Am 2006;88:47-54.
98. Berend ME, Ritter MA, Meding JB, et al. Tibial component failure mechanisms in total knee arthroplasty. Clin Orthop Relat Res 2004;428:26-34.
99. Viskontas DG, Skrinikas TV, Johnson JA, et al. Computer-assisted gap equalization in total knee arthroplasty. J Arthroplasty 2007;22:334-42.
100. Gamada K, Jayasekera N, Kashif F, et al. Does ligament balancing technique affect kinematics in rotating platform, PCL retaining knee arthroplasties? A prospective randomized study. Knee Surg Sports Traumatol Arthrosc 2008;16:160-6.
101. Insall JN, Binazzi R, Soudry M, et al. Total knee arthroplasty. Clin Orthop Relat Res 1985;192:13-22.
102. Crottet D, Maeder T, Fritschy D, et al. Development of a force amplitude- and location-sensing device designed to improve the ligament balancing procedure in TKA. IEEE Trans Biomed Eng 2005;52:1609-11.