Dynamic Soft Tissue Balancing in Total Knee Arthroplasty

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KEYWORDS
- Total knee arthroplasty • Sensor • Soft-tissue balancing • Smart tibial trials • Dynamic balancing • Balancing verification

KEY POINTS
- Historically, ligamentous tension and laxity have not been measured and thus have not been quantified to correlate with patient outcomes.
- Intraoperative sensors can guide and confirm correction of soft tissue imbalance.
- Intraoperative sensors can communicate the effects of implant alignment and rotation on soft tissue balance.
- Intraoperative sensors allow the evaluation of the effects of implant kinematic design on the kinetic profile of the knee joint.

LIGAMENTOUS IMBALANCE AND INCIDENCE OF REVISION

A successful total knee arthroplasty can alleviate pain and reestablish proper kinetics to an arthritic joint.1–3 This highly effective procedure is performed in more than 500,000 new patients in the United States every year, and this number is expected to reach 3.48 million by 2030.4

Although the survivorship of total knee arthroplasty components is greater than 90% at 15 years, the revision burden (defined as the ratio of revision to the total number of arthroplasties) has not improved for the past decade.5–7

The clinical and economic implications for revision surgery are underappreciated. More than 55,000 revision surgeries were performed in 2010 in the United States, with 48% of these revisions performed in patients younger than 65 years. Total costs associated with each revision total knee arthroplasty have been estimated to exceed $49,000. The current annual economic burden of revision knee surgery is $2.7 billion in hospital charges alone. By 2030, assuming a 5-fold increase in the number of revision procedures, this economic burden will exceed $13 billion annually.5

The number of revision total knee arthroplasties is expected to continue to increase, in concert with the rapidly increasing number of primary procedures, over the next 20 years.4 Thus, new technologies that limit the factors associated with an increased risk of revision are now paramount to both the continued success of primary total knee replacement and reducing the economic burden associated with revision procedures themselves.

Joint infection is still the foremost cause of early revision. However, instability, malrotation, malalignment, component loosening, and patellofemoral complications all result from surgical technique that inadequately addresses soft tissue balance.6–9

Instability is cited in up to 22% of reported reasons for revision.7 In patients exhibiting instability, excessive laxity in the soft tissues can cause pain, effusions, and an inability to navigate curbs and inclined planes.8

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Component loosening (up to 17% of early-stage revision; 34% of late-stage revision) is often a secondary effect of accelerated polyethylene wear. This polyethylene microdebris disseminates into the joint space and causes an inflammatory immune response. This inflammation results in osteolysis and disintegration of the bone–component interface. Accelerated wear is seen in patients with excessive soft tissue tension medially, laterally, and in the flexion gap from an excessively tight posterior cruciate ligament (PCL). Malalignment and patellofemoral complications caused by maltracking can lead to anterior pain, patellar instability, patellar fracture, and tibiofemoral flexion instability. These complications can occur from tibiofemoral rotational incongruency, commonly caused by internal rotation of the tibial tray, femoral component, or both. Reducing the occurrence of these soft tissue related complications is essential for minimizing the percentage of revision procedures after total knee arthroplasty. Real-time data, presented intraoperatively, can assist the surgeon in reducing surgical outliers and achieving a well-aligned and well-balanced knee.

DEFINING BALANCE

Traditional Methods for Defining Balance

To achieve gap balance, most surgeons typically use spacer blocks to confirm that the extension and flexion gaps of the joint are equal with respect to a fixed distance measurement. This gap measurement dictates composite thickness of the final implant. Surgeons then rely on tactile navigation with their own hands, assessing coronal plane balance through applying a varus-valgus moment to the joint and evaluating the relative opening in each compartment.

Spacer blocks provide information on joint gaps and the alignment of cuts, but are not sensitive to soft tissue balance in the sagittal plane. When using spacer blocks, defining coronal intercompartmental balance in mid flexion and full flexion is often inconsistent, secondary to the open capsule, a subluxed patella, and hip rotation.

Surgical approaches to prepare the knee joint for the final prosthesis vary based on surgeon training and instrumentation. The 2 standard methods that are well documented are:

1. Measured resection: a technique in which the surgeon makes all bony cuts based on anatomic references, then uses the trial implants to balance soft tissue tension.

2. Gap balancing: a technique in which the extension gap is balanced after the distal femur and proximal tibia are resected. The flexion gap is then distracted at 90°, allowing ligament tension to guide the femoral rotation.

Several factors contribute to inaccuracy in restoring normal balance and alignment in total knee arthroplasty when using either of the previously mentioned techniques. First, bony landmarks currently used to determine femoral rotation have been shown to be inaccurate, particularly in a deformed arthritic knee. Soft tissue releases do not always affect flexion and extension gap balance symmetrically. Finally, optimizing tibiofemoral balance can sometimes negatively affect patellofemoral tracking.

The difficulties in achieving balance persist despite the availability of the techniques described earlier, because determining the degree of ligament balance in total knee arthroplasty has traditionally been established by the subjective assessment of each surgeon. Surgical results achieved by these subjective methods have been variable without the availability of intraoperative data to correlate techniques to outcomes. Until recently, no method was available with which to quantify the relative “feel” of a joint when guiding soft tissue release.

Novel Methods and a More Precise Definition of Balance

Technological advances in microelectronics have only recently made it possible for the surgeon to quantify how ligamenture surrounding the joint directly affects articular kinetics through a full range of motion. This new sensor-embedded technology allows the surgeon to adjust for soft tissue imbalance, while receiving dynamic visual feedback regarding the specific knee design, within each patient-specific soft tissue envelope. For the first time, subjective surgeon assessment can be quantified, and balance in the coronal and sagittal planes is verifiable.

The sensor-embedded microelectronic array is housed in the standard tibial insert (Fig. 1) to identify the effects of alignment, rotation, and ligamentous tension or laxity on the geometric design of the knee.

Clinical and biomechanical analyses have shown that optimal joint kinematics are best evaluated with the patella reduced and the medial capsule closed. The knee is taken through a full range of motion, and the intercompartmental load differential is examined in early flexion, mid flexion, and full flexion to detect coronal
plane asymmetry. The femoral rollback and posterior drawer is tested while the femoral contact points are evaluated to assess sagittal plane stability.

The development of sensor-embedded technology has allowed the construction and verification of a more scientifically based definition of balance. A new definition of soft tissue gap is exhibited from 10° to 110° of flexion. In terminal extension, the effects of compression, the screw-home mechanism, and the posterior capsule mask the effects of soft tissue tension or laxity (Figs. 2–4).

Therefore, the most useful application for this intraoperative data is to apply it to the evaluation of subtle joint imbalance, tibiofemoral rotational incongruency, and component malalignment.

**CLINICAL APPLICATIONS FOR DYNAMIC SOFT TISSUE BALANCING**

**Rotational Incongruency**

Tibiofemoral rotational incongruency in total knee arthroplasty is associated with anterior knee pain, poor kinematic function, unfavorable patellar tracking, and decreased implant survivorship. In one particular study, arrack and colleagues showed that as little as 4.6° of internal rotation can cause anterior knee pain. Additionally, Berger and colleagues reported that 5° to 8° of tibiofemoral rotational incongruency leads to patellar maltracking.

To establish an appropriate rotational orientation of the femoral component, anatomic reference points are commonly used. Flexion distraction technique is also used to obtain a parallel flexion gap using the ligament tension in flexion to determine the femoral rotation.

When aligning the tibial tray, the mid to medial third of the tibial tubercle is commonly used. However, errors have been reported when using this landmark, because of a wide variance of up to 25° of rotation inherent in the line between tibial tubercle and posterior tibial plane.

A retrospective analysis of intraoperative data from 100 consecutive total knee replacements found that 63.1% of patients exhibited an average of 6.3° ± 4.3° of asymmetrical tibiofemoral

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**Fig. 1.** Intraoperative knee showing replacement of the standard tibial trial with an “intelligent” trial.

**Fig. 2.** Terminal extension with higher loads displayed on the medial side.

**Fig. 3.** Balanced loading at 10° flexion.

**Fig. 4.** Balanced loading at 90° flexion.
contact-point positioning in extension. Tibial tray rotation for all patients was initially dictated by the location of the mid-third of the tibial tubercle. Guided by intraoperative sensor feedback, the surgeon was able to correct all rotational incongruency in every case.30

Through incorporating intraoperative sensors, surgeons can set the rotation of the components using any method of their choosing. When the components are in place, any remaining tibiofemoral rotational incongruency can be corrected for using the location of femoral contact points, as shown dynamically on-screen by the sensor system.

With the placement of an anterior-medial or lateral pin to control for potential translation of the tray across the tibial plateau with trialing, the surgeon adjusts the tibial tray rotation until alignment of the femoral contact points is achieved (Fig. 5). These adjustments are evaluated and confirmed in real time. Central patellar tracking is then confirmed and the tray is pinned and stabilized. Optimal congruency is important to define before kinetic rollback and soft tissue balance are assessed. It is also seen that when the femoral condyles are relocated to the central tibial plateau and the femoral contact points are below 5° of rotation, soft tissue tension commonly equalizes. The belief is that this mechanism will improve anterior knee pain and stability through a full range of motion.

Appropriate rotational congruency is important for the survivorship of total knee arthroplasty components and, as suggested by literature, is difficult to attain.26–29 Thus, advanced methods, such as using intraoperative sensors, may prove more useful than establishing references based on anatomic landmarks, which are inherently prone to variability.

**Joint Imbalance**

**Coronal plane imbalance**

During primary total knee arthroplasty, the surgeon may encounter excessive medial or lateral collateral ligament tension while addressing a varus or valgus knee. This excessive tension leads to increased loading in the medial or lateral compartment, which can be seen through a full range of motion. If uncorrected, the induced joint imbalance can culminate in unfavorable clinical outcomes, including pain, accelerated polyethylene degradation, joint instability, and limited range of motion.10

Although most surgeons can detect gross instability, judging ligament tension is difficult. However, the integration of intraoperative, sensor-embedded tibial inserts provides a way to evaluate tissue tension, and selectively optimize its release.

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**Fig. 5.** (A) The knee is taken into extension and tibiofemoral incongruency is shown. (B) Surgeon adjusts the tibial trial to align femoral contact points; intercompartmental equalization of loads is achieved with correction of mal-rotation alone. The arrows are pointing out the location of femoral contact points on the tibial trial surface.

**Fig. 6.** (A) Surgeon identifies excessive medial pressure in mid flexion. (B) He selectively pie crusts the anterior bands of the medial collateral ligament to equalize loads in flexion, while avoiding anterior compartmental effects.
As part of an Institutional Review Board–approved multicentric evaluation, 232 patients were evaluated intraoperatively for joint imbalance (with imbalance defined as a mediolateral intercompartmental loading difference of $\leq 15$ lb). Using intraoperative-sensor feedback, soft tissue release was deemed necessary in 92.6% of patients to achieve balanced kinetics.31

Using the intraoperative sensors, surgeons can evaluate femoral contact point position and mediolateral intercompartmental loads (measured in pounds). Coronal asymmetric imbalance in flexion, mid flexion, and extension can now be recognized and defined. These data supplement any applied stress testing and allow the surgeon to close the medial capsule to identify the real soft tissue tension in flexion. If necessary, the surgeon can selectively titrate ligaments in a gradual fashion to avoid underreleasing or overreleasing (Fig. 6).

If medial or lateral imbalance is encountered, the surgeon may use the pie-crusting technique described by Bellemans and colleagues.20 With this method, the surgeon first palpates the tissue to evaluate any fibers en tensio. Then, an 18-gauge needle is used to sequentially pierce the structure of the ligament, perpendicularly to its fibrous growth pattern, releasing it to a balanced state (Fig. 7). This gradual release of fibers is tracked on-screen by the sensor system, and allows the surgeon to witness the dynamic change in load pressure.

Using a modified releasing technique, with real-time sensor data, the surgeon can release tension in the collateral ligamenture with quantified dynamic feedback. This gradual, digitally guided ligamentous release may prove to be a safer method than traditional transections, which may lead to underrelease or overrelease. Using a data-driven technique, the surgeon can confirm that both compartments of the bearing surface are loading proportionately in a selective approach.

**Sagittal plane imbalance**

Total knee arthroplasty components that incorporate a posterior substituting or cruciate retaining design have shown excellent long-term clinical results.4 However, imbalance in the sagittal plane can still present with well-aligned implants. Although flexion instability may be seen more commonly in a PCL design, revision studies show that Posterior Stabilized (PS) designs can exhibit instability, especially in the posterior lateral corner during a flexion varus moment (ie, putting on shoes). Symmetric imbalance is typically seen with an overresected posterior femur, excessive tibial slope, or incompetent PCL, whereas an asymmetric imbalance is seen with improper femoral rotation or an overtensioned PCL.32

A balanced sagittal plane exhibits neither excessive tension nor laxity of the PCL. When taken into passive flexion, the femoral component undergoes symmetric rollback without anterior lift-off of the tibial insert (Fig. 8).

When evaluating flexion gap stability, it is imperative to reduce the patella and close the medial capsule to minimize error in assessing stability. A posterior drawer test is applied at 90° of flexion and the femoral contact points are evaluated. In a
stable knee, the contact points should remain in the central third of the bearing surface with minimal translation (Fig. 9).

Sagittal plane imbalance, which commonly leads to early revision, presents as excessive PCL tension or flexion gap instability. Both intraoperative presentations are discernable, and can be corrected for, using sensor-embedded technology.

Excessive tension in the PCL is displayed through the sensor system as (1) an extreme posterior position of the femoral contact points, and (2) excessive loading in the posterior compartment during flexion. On application of a posterior drawer test, no excursion of the femorotibial contact points is detected.

If excessive loading presents in the posterior-medial compartment alone, this is indicative of required release of the PCL (Fig. 10).

When excessive loads are exhibited in both compartments simultaneously (symmetric imbalance), additional tibial slope can be added (Fig. 11).

Symmetric flexion instability can present in either the early or late postoperative phase, secondary to a rupture of the PCL.

Using the femoral contact-point tracking option of the sensor system, relative motion of the distal femur to the proximal tibia can be dynamically displayed during the posterior drawer test. Excessive excursion of the femoral contact points across the bearing surface (Fig. 12) and femoral contact points translating through the anterior third of the tibial trial are an indication of laxity in the PCL. Surgical correction requires the use of a thicker tibial insert, anterior-constrained insert, or a posterior-stabilized knee design.

Using sensor technology to guide the surgeon through appropriate sagittal plane correction, the subtleties in imbalance or suboptimal bone cuts can be accounted for, which otherwise may be overlooked by traditional methods of subjective surgeon “feel.”

Malalignment

Malalignment leads to early failure and implant loosening, and recent data have challenged the importance of the 3° range of alignment. The outcomes presented in these studies may have been avoided with the ability to evaluate the critical elements of soft tissue balance and rotation.

Fig. 9. The surgeon applies a posterior drawer test and sees minimal translation of the femoral contact points, indicating flexion gap stability.

Fig. 10. (A) In this clinical case, excessive medial femoral rollback is seen with increased loads. (B) The PCL is dynamically pie-crusted and the knee re-cycled. (C, D) The flexion gap is now balanced, the medial femoral contact point centralized and a stable posterior drawer is seen to be stable on testing.
suboptimal data of which may be an indication of component malalignment (Fig. 13).

The advancement of implant design, polyethylene composite, and cementing techniques will affect implant function and longevity, although this will primarily depend on patient selection and surgical technique. Achieving a successful outcome is a complex amalgam of coronal and sagittal alignment, balance through a full range of motion, and optimized implant congruency and rotation.

THE FUTURE OF SOFT TISSUE BALANCING

The future of joint balancing will incorporate component rotation and alignment into the evaluation of soft tissue balance. Using one device that is constructed based on the geometric design of the implant will allow the surgeon to make real-time adjustments to all of these parameters, and witness how they affect patient soft tissue balance.

The ability to incorporate predictive shims will allow surgeons to evaluate, on a degree-by-degree scale, how varus-valgus alignment or tibial slope can alter the kinetic signature of the knee before they make adjustments. This assessment will lead to predictive modeling for each pathologic knee condition. The development of these algorithms will then enable the computer to help the surgeon decide which possible corrective maneuvers are most appropriate for current imbalance, while providing dynamic feedback as the corrective techniques are performed.

The large-scale collection of intraoperative data, coupled with patient demographic and surgical information, will help establish a national orthopedic registry. With a registry in place, a thorough analysis of outcomes, based on the multifactorial

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Fig. 11. (A) In this clinical case, excessive flexion loads are seen with excessive femoral rollback. The arrows are pointing out the location of femoral contact points on the tibial trial surface. (B) Two degrees of slope were added to optimize the flexion gap. (C) Rollback is optimized. (D) Posterior drawer shows excellent stability.

Fig. 12. (A) Excessive femoral translation is seen with a posterior drawer. (B) The surgeon adds 2 mm of thickness to the tibial trial and a stable flexion gap is achieved.
aspects of knee replacement surgery, can be performed.

The full potential of sensor use in arthroplasty will be actualized when the implants themselves become embedded with microelectronics. This technique will help close the loop on how surgical technique directly affects the function and longevity of the total knee replacement.

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Fig. 13. (A, B) In this clinical case of tibia vara, the surgeon sees excessive loads medially in both the flexion and extension gaps. (C) Before performing any releases, he checks his tibial and femoral cuts and sees that he is in slight valgus, which adds to the medial tightness. He elects to add more varus to his tibial cut. (D, E) Optimal loads and gap kinematics have been achieved through a full range of motion.


