

Principles of Ligament Balancing in Total Knee Replacement

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Knee ligaments function as viscoelastic cords whose mechanical character is described by a force/displacement curve. The key ligaments for total knee replacement are the superficial medial and lateral collateral ligaments as they are important stabilisers throughout the range of motion. The posterior cruciate ligament is an important check rein of the knee and flexion laxity is increased significantly with its release. Surgeons must consider the different situations that arise when they choose to preserve or sacrifice the posterior cruciate ligament. New technologies are available; sophisticated mechanical tensors, computer navigation algorithms, and digitally instrumented tibial trial inserts that will allow the surgeon to better understand surgical variables and to add precision to their surgical techniques.

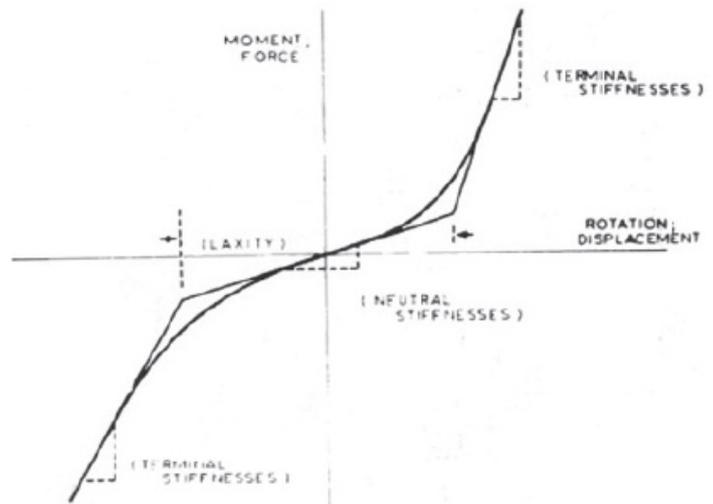


Figure 1 - Ligament biomechanical function described by a force/displacement curve with zones of laxity and terminal stiffness with transition defined as "breakpoint".

²Instability of ligaments is a direct consequence of inadequate balancing performed during the surgical procedure. Fehring, et al reported that 27% of patients who required revision surgery within five years of the index operation suffered from chronic ligamentous instability.¹ Sharkey, et al found 21% of early and 22% of late revisions were caused by instability. From an educational point of view, an important approach to correct this problem is to improve the surgeon's general understanding of the relevant issues involved. This review surveys the topics of anatomy, clinical outcome studies, and new instrument technologies and elaborates on the important concepts of balancing.

Anatomical Studies

Markolf, et al described the mechanical features of ligament function as a viscoelastic structure that stretches much as a stiff bungee cord. Ligament stretch is characterised by a force displacement curve where laxity changes with load to terminal stiffness over a brief zone defined as the breakpoint.³ (Figure 1). Surgeons can feel the 'mushy' zone and easily assess stiffness, but have a poor sense of the ligament strain that occurs in the zone of stiffness. As ligaments are such stout structures, the strain definition of terminal stiffness has little clinical relevance. >>



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Kennedy, et. al. measured the load to failure of the important knee ligaments finding that the superficial collateral ligament withstood 467 Newtons of maximum load, the anterior cruciate ligament about 472 N, and the posterior cruciate ligament at 920 Newtons.⁴ It could be stated that the ligaments are either 'loose' or 'tight', basically a binary solution. This is an important concept for today's new technologies that have been introduced such as mechanical tensors and sensors that are able to define loads or displacements over very small margins.

Good, et al found that in extension, the overall varus/valgus laxity averaged 6.5°. The medial and lateral collateral ligaments provided about 50% of the constraint in extension, increasing to nearly 80% as the knee flexed. The cruciate ligaments were secondary stabilisers providing 14% of the constraint in full extension. Most other structures including the hamstring muscles, iliotibial tract, and posterior capsule were active only in extension. Whiteside performed numerous cadaveric studies with a novel test jig that could assess displacement or the effects of ligament stability throughout the range of motion under a constant load of 10 Newtons/metre and also had the ability to add a 1.5 Newton/metre rotational load.⁶⁻⁹ (Figure 2).



Figure 2 - Original ligament tensor rig developed for Dr Leo Whiteside, which has been updated with state of the art digital integration (image courtesy Dr William Mihalko, 2014)

The collateral ligaments were found to be important stabilisers in all positions. The anterior cruciate ligament was active primarily in extension providing about 3.5° of varus/valgus stability, while the posterior cruciate ligament was active primarily in flexion, providing about 3.5° varus/valgus of stability. Krakow, et al found that PCL absence created about 50% higher laxity in flexion¹⁰. These findings have important implications for different approaches that save or preserve the posterior cruciate ligament.

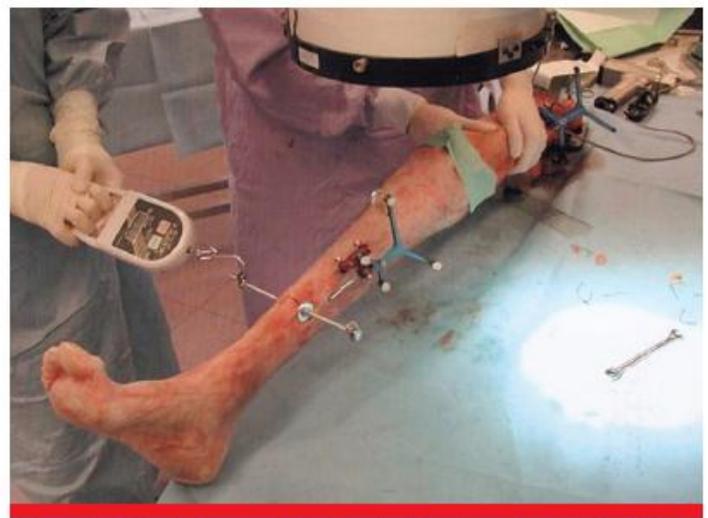


Figure 3 - Test setup for measuring 'normal' cadaver ligament gaps using a 10 newton/meter load and computer navigation for data acquisition (Von Damme)

Simply stated the tight check rein provided by the posterior cruciate ligament diminishes the potential for flexion laxity. This allows surgeons to use measured resection bone cuts (cruciate retaining knees) for the femoral anterior/posterior cut, despite the variability in anatomical variation into posterior condylar offset known to exist with these methods. Posterior cruciate sacrifice adds significant laxity to the flexion gap by removing the check rein that must carefully be accounted for. Insall and Ranawat recognised the importance of balancing the knee in extension and flexion as a guiding principle to prevent instability^{11,12}.

Gap balancing as was developed by Insall and Ranawat comes from the need to balance the medial and lateral collateral ligaments and then create bone resections that allow for rectangular symmetrical gap spaces in flexion and extension. Several distraction devices have been produced that measure in

flexion and extension reproducing a ligamentous tension between 70 and 180 Newtons²³ et al. A recent 'normal' cadaver study using computer navigation by Von Damme, et al confirmed the typical kinematic features of ligament function by noting 2 to 3 degrees of laxity in extension which increased to six to eight degrees when measures in flexion with more laxity in the lateral compartment.¹³ (Figure 3).

Recent clinical studies have looked at ligament stability of postoperative total knee patients in full extension measuring in the coronal plane¹⁴⁻²⁰. These studies show medial and lateral laxity to be approximately four degrees or four millimetres. There was no difference in clinical outcome with choice of implants, surgical technique, cruciate retaining or sacrifice, or with the balancing method. This instability is lower than the Von Damme cadaver study mentioned earlier, which showed tighter stability in extension of normal knees.



Figure 4 - Test setup for metrology validation of ligament gap repeated measures study evaluating a bone morphing software protocol used with computer navigation.(Stiehl)



Figure 5 - Test setup for repeated measures study of ligament gaps distracted by simple tensor.

Tokohura used MRI or shoot through radiographs to look at flexion instability and found that the flexion gap varied from 1-6 mm with asymmetric widening on the lateral side.^{21, 23}

Thompson, et al utilised an experimental model to assess ligament strain caused by abnormal femoral rotation using tissue tensioning techniques²⁴ When the femoral component was rotated up to 15° of internal rotation, which falls within the known range of clinical outliers, the strain in the superficial medial collateral ligament at 90° flexion increased to nearly 450 Newtons which we know is the failure point of this ligament.(Figure 5) Though theoretical, this study allows us to understand the painful consequences for the patient of a ligament that was abnormally balanced by poor implant

placement. Certainly, this explains one mechanism for clinical stiffness where the patient simply finds his knee too painful to bend.

Matsumoto, et al investigated the effect of the extensor mechanism on ligament stability intra-operatively using a calibrated tensor that could measure gaps and forces through the range of motion.²⁵ (Figure 6). Reduction of the patella and extensor mechanism produced increased stability at least with posterior cruciate retaining knees. Muratsu, et al used a tensor to assess the effect of prosthetic components on the gaps finding the posterior condyles significantly tightened the extension gap and caused almost 5° of flexion.²⁶ Several recent studies have evaluated intraoperative ligament stability through the range of motion rather than static flexion or extension using either a mechanical tensor or computer navigation. Hino, et al found greater laxity overall

in posterior stabilised knees when examined with computer navigation which was particularly marked at 30° flexion.²⁷ Minoda, et al used a mechanical tensor and showed similar patterns of instability through flexion.²⁸ Assessing gap balance in extension or 90° flexion may not give the true picture of overall stability. Cross et al studied the effect of elevating the joint line on ligament stability in a model where there was a need to elevate the joint line.²⁹ Notably, the higher

the joint line, the greater amount of mid-plane flexion laxity was seen. Additionally, other issues, posterior condyle offset, joint line position, distal femoral geometry, and ligament balancing methods may be relevant. Only by studying these additional variables may we find key factors that may lead to outliers in a given scenario. >>

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Figure 6 - Data automated tibial tray sensor that measures range of motion, condyle contact point, and load, and is used for ligament balancing after trial component placement. (Courtesy Orthosensor, Fort Lauderdale, FL)

Future Directions

Several new tensor technologies have been presented. Mechanical devices are available that are designed to control the distraction of the gaps and to define the tilt of the asymmetrical gap using standardised tensions; using a new computer navigation system which can measure throughout flexion. We developed a bone morphing protocol that allowed precise gap measure of the medial and lateral gaps at each degree of flexion through the range of motion. We found that in cadaver knees there were significant differences in each specimen's medial and lateral joint space gaps when comparing five degree flexion points through the range of motion. Additionally, there was high variability from specimen to specimen. All knees were tightest in full extension but became more lax after 10° of flexion. More importantly, we could find that choosing points of flexion at 0 degrees and 90 degrees did not always describe

the overall laxity 'footprint' for that cadaver.

Other recent technology includes the instrumented tibial insert (Verasys, Orthosensor, Sunrise, FL),³¹ (Figure 8), which has demonstrated interesting results. Contact point, range of motion, and the applied load onto the device surface reflecting the ligament tension of the implanted devices can all be measured throughout movement on the operating table. Walker, et al studied cadavers with implanted total knee prosthetics using this device assessing a variety of surgical variables such as ligament tightness from prosthetic stuffing or abnormal bone cuts, femoral condyle offset and joint line elevations.³² The pretension status of a knee that had been 'perfectly balanced' clinically by a surgeon had a medial and

lateral load of about 145 Newtons, reflecting the weight of the leg. Small changes in gap distance of one to two millimetres caused dramatic changes in the ligament tension or the load applied to the surface of the instrumented insert (Figures 4 & 5).

Conclusions

The medial and lateral collateral are the key ligaments to address with total knee surgical technique. They are the only ligaments structures that are key stabilisers throughout the full range of motion. If the posterior cruciate is retained measured resection techniques work well because of the tight check rein of the PCL controlling the flexion space. The surgeon must be concerned primarily with tibial slope and balance through the range of motion to prevent the 'too tight' or 'too loose' scenario in flexion.

Posterior cruciate sacrifice creates significant flexion space laxity which is greater throughout the range of movement. Gap balancing using technology that carefully measures the flexion space after initial ligament balancing is more precise in creating the optimal construct.

New, emerging technologies will help the surgeon understand these issues and make the best surgical choices. ■

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