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.

Instability 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. 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 “breakpoint.” 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.
Kennedy, et. al. measured the load to failure of the important knee ligaments finding that the superficial medial collateral ligament withstood 467 Newtons of maximum load, the anterior cruciate ligament about 472 N, and the posterior cruciate ligament at 920 Newtons. 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.

Grood, 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).

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.

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 instability11,12.

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.
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.\textsuperscript{21, 23}

Thompson, et al utilised an experimental model to assess ligament strain caused by abnormal femoral rotation using tissue tensioning techniques.\textsuperscript{24} 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.\textsuperscript{26} (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.\textsuperscript{27} (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.\textsuperscript{28} 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.\textsuperscript{27} Minoda, et al used a mechanical tensor and showed similar patterns of instability through flexion.\textsuperscript{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 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. \textsuperscript{30}
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placement. (Courtesy Orthosensor, Fort Lauderdale, Fl)

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 direction
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
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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), 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. 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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