



Review

Clinical biomechanics of instability related to total knee arthroplasty

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ABSTRACT

Background: Tibiofemoral instability is a common reason for total knee arthroplasty failure, and may be attributed to soft tissue deficiency and incorrect ligament balancing. There are many different designs of implant with varying levels of constraint to overcome this instability; however there is little advice for surgeons to assess which is suitable for a specific patient, and soft tissue balance testing during arthroplasty is very subjective.

Method: The current theories on primary and secondary soft tissue restraints to anterior/posterior, varus/valgus, and internal/external rotational motion of the knee are discussed. The paper reviews biomechanics literature to evaluate instability in the intact and implanted knee.

Findings: The paper highlights important intra- and extra-capsular structures in the knee and describes the techniques used by clinicians to assess instability perioperatively. In vitro cadaveric studies were found to be a very useful tool in comparing different implants and contributions of different soft tissues.

Interpretation: In vitro cadaveric studies can be utilised in helping less experienced surgeons with soft tissue releases and determining the correct implant. For this to happen, more biomechanical studies must be done to show the impact of release sequences on implanted cadavers, as well as determining if increasingly constrained implants restore the stability of the knee to pre-deficient conditions.

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1. Introduction

The use of total knee arthroplasty (TKA) to combat the effects of osteoarthritis has become standard practise for many years. From a survey of 18 different countries, it has been estimated that annually there are 175 total knee procedures for every 100,000 people in the population (Kurtz et al., 2011).

Yet despite being a common procedure, failures of the TKAs are possible, and revision surgery to a more constrained design inevitably presents additional health and emotional issues for the patients as well as financial implications (Sharkey et al., 2002). A major reason for failure is instability, defined as excessive and unnatural movement of the implant components (Rodriguez-Merchan, 2011) which may occur within weeks, months or even many years after the initial surgery.

Sharkey et al. (2002) performed a retrospective review over a three year period at one institution, and found that instability was a major reason for surgery in 21.2% of early stage revisions (occurring less than two years after primary arthroplasty) and 22.2% in late stage revisions. A similar situation was noted in a multicentre prospective cohort

study by Mulhall et al. (2006), who found that 28.9% of patients who required revisions suffered from instability.

Instability may be a result of initial and progressive soft tissue deficiency, inadequate soft tissue and gap balancing during surgery, component misalignment, and inappropriate implant restraint, size and design (Mulhall et al., 2006; Sharkey et al., 2002; Vince et al., 2006; Yercan et al., 2005). To prevent instability in TKAs, improvements in surgical technique and TKA design can be enacted with knowledge of how soft tissue deficiency affects the stability after implantation. This review sets out to discuss how laxity/instability of a TKA-implanted knee joint can be measured, evaluate different methods of experimentation, and present the current ideas of ligamentous and soft tissue restraint to major planes of knee motion.

2. TKA designs

Condylar total knee designs in their current recognisable form have been developed since the 1970s (Robinson, 2005): a metal femoral prosthesis; a metal tibial tray with a proximal polyethylene articulating surface; and occasionally a polyethylene patellar component.

There are a wide variety of TKA designs available, varying in degrees of constraint, bone loss and soft tissue resection. For uncomplicated primary knee replacements the most commonly used types are the cruciate-retaining (CR) and posterior-stabilised (PS) designs. A CR TKA

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requires resection of the anterior cruciate ligament (ACL) but retains the posterior cruciate ligament (PCL). This type of TKA usually derives stability by having concave articular surfaces on both medial and lateral tibial condyles, which act to locate the femoral condyles under the influence of axial joint compression. Both the conformity of the articulation, and the tensions in the surrounding ligaments, reduce knee laxity (Ishii et al., 2011). The depth and slope of the concavity of the tibial bearing contribute to the inherent stability of the prosthesis, and that may be characterised by force versus displacement testing of the prosthesis whilst subjected to axial compressive loading (ASTM standard F1223, 2008; Haider and Walker, 2005). Increased soft-tissue tension may reduce tibiofemoral laxity, but excessive tension is undesirable; in the CR TKA, for example, the unbalanced tension in the PCL causes tibial anterior subluxation, so that the femoral component bears onto the posterior edge of the tibial articular surface (Heesterbeek et al., 2010a,b).

A posterior-stabilised (PS) design removes both cruciate ligaments and instead utilises a post-box-cam mechanism to prevent non-physiological anterior movement of the femur with respect to the tibia when flexed (Fantozzi et al., 2006; Walker et al., 2009). An argument for the implantation of a PS over a CR design is that collateral ligament balancing is more easily achieved than with a CR design (Freeman and Raiton, 1988). The post-box-cam mechanism of a PS-implanted knee drives femoral posterior roll-back in knee flexion, which delays posterior impingement and thus leads to greater knee flexion (Jacobs et al., 2005). The fit of the tibial post into the 'box' between the femoral condyles also limits tibial internal–external rotation.

Less-common designs retain both cruciate ligaments in an attempt to retain knee kinematics which are as close to physiological behaviour as possible (Cloutier et al., 1999). It is unusual for a TKA to incorporate ACL retention, despite the importance of the ACL for stability of the natural knee. This situation arose because, in the era when the TKA procedure was being developed, it was reserved for those with chronic, severe arthritis, and so the ACL was usually incompetent in the presence of degenerative changes such as impinging osteophytes.

Other variations of TKA include mobile-bearing designs where the polyethylene insert can rotate and slide freely on the tibial tray (Most et al., 2003a). More recently, designs have incorporated asymmetrical femoral condyles. These designs have highly stable medial condylar articulations and lateral articulations which allow for more anterior/posterior freedom, which is believed to replicate more anatomically-correct knee kinematics (Amin et al., 2008; Walker et al., 2010).

If a TKA fails and requires revision, or the patient has multiple ligament or bone deficiencies even before a primary operation (Yang et al., 2012), more constrained condylar knee designs may be implanted. These usually include longer intramedullary stems and larger, more squared tibial posts than a PS design. Further restraint against global instability may be introduced with rotating-hinged designs (Yang et al., 2012), in which the tibial and femoral components are linked together.

3. Primary and secondary ligamentous and soft tissue restraints

The complex network of ligaments and soft tissue surrounding the knee and within the capsular structure can be classified into primary and secondary stabilisers. A primary restraint can be seen to be the main passive restraint to motion in a specific degree of freedom (DOF) (Noyes et al., 1980), with secondary restraints that resist the motion to a lesser degree. However, the secondary restraints may become a major stabiliser in the cases when primary restraints are deficient or require resection, for example in many arthroplasty designs. Therefore, understanding how the ligaments and soft tissues interact in the different planes of motion is beneficial for any investigations into TKA instability.

Table 1 lists various papers that investigated ligamentous and soft tissue restraints on intact knees using a variety of in vitro and in vivo

methods. There has been less research, however, into the soft tissue restraints post-TKA (Table 2). Literature was searched from the Medline database via PubMed using the following keywords: knee instability, primary knee restraints, ligamentous and soft tissue restraints, anterior/posterior laxity, medial/lateral laxity. From those, the listed papers were chosen because they included very precise details about what method of in-vivo, in-vitro or in-silico testing was undertaken, distinct definitions of which soft tissues were being investigated, and clear descriptions of the test methods that were performed, that would allow a reader to reproduce them if so desired.

3.1. Anterior translation

It has been well established that the primary restraint to anterior translation of the tibia relative to the femur is the ACL, with Butler et al. (1980) reporting an average 86% of the total resisting force against anterior drawer was provided by it (Fig. 1). The ACL is nearly always resected in TKA implantation, and so designs must incorporate more conforming articulating surfaces to prevent excessive anterior slide of the tibia.

Butler et al. (1980) and Sullivan et al. (1984) described the medial collateral ligament (MCL) as a significant secondary restraint to anterior drawer, a finding supported by Sakane et al. (1999), who reported that the MCL contributed around 60% of the total restraint the ACL carried at 90° flexion. Additionally, other studies highlighted the role of the iliotibial band (ITB) as an 'ACL agonist' (Yamamoto et al., 2006) and, provided the ACL is resected first, the secondary restraint from the medial meniscus (MM) (Allen et al., 2000; Levy et al., 1982). The lateral meniscus (LM) was found not to be a significant restraint (Levy et al., 1989).

3.2. Posterior translation

The PCL is the primary restraint to posterior translation of the tibia (Fig. 2), offering on average 95% of the total resisting force in the flexed knee (Butler et al., 1980); Race and Amis (1996) showed that this contribution fell as the knee extended, leaving the posterolateral structures (PLS) to resist posterior translation near full extension. Other authors agreed that the PLS comprising of structures such as the popliteus tendon (Pop T) and the popliteofibular ligament (PFL) act as secondary restraints to tibial posterior translation (Butler et al., 1980; Gollehon et al., 1987).

Whilst the PCL is retained in CR TKAs, a PS TKA resects the PCL and instead utilises a vertical post on the tibial plateau, which engages with a femoral box in flexion, and prevents the tibia from sliding posteriorly relative to the femur (Fantozzi et al., 2006). Some instability may result near knee extension (the weight-bearing posture) if the post-box mechanism only engages in deeper knee flexion which is typically around 50° flexion.

On the medial side of the knee, Robinson et al. (2006) observed the posteromedial capsule (PMC) being well aligned to resist posterior translation at full extension. This was supported by Petersen et al. (2008), who also defined a posterior oblique ligament (POL) between the MCL and PMC as producing significant restraint at all angles of flexion between 0–90° flexion (it is debated whether such a distinct band exists (Amis et al., 2003)). Additionally, Gupta et al. (2003) found the ligaments connecting the LM to the posterior aspect of the femur (the meniscomfemoral ligaments of Humphry and Wisberg) to be secondary restraints to posterior drawer, contributing 28% of the restraint at 90° flexion; they are resected during TKA.

3.3. Valgus rotation

The superficial medial collateral ligament (sMCL) is the primary restraint to tibial abduction, which manifests as medial opening of the knee (Fig. 3) (Grood et al., 1981). Robinson et al. (2006) discovered

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