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.
Dear Professor Kim Burton and colleagues,

Re: Manuscript entitled ‘Clinical biomechanics of instability related to total knee arthroplasty’

I am pleased to be submitting this literature review to Clinical Biomechanics. I hope that you find the manuscript an interesting and strong addition to the journal and the field of biomechanics.

There is no duplicate publication elsewhere of any part of the work and no related paper previously published in Clinical Biomechanics. Imperial College London has received money from Stryker Corporation to fund this project. The typescript has been read and agreed by all authors, and the corresponding author is Andrew A Amis (Department of Mechanical Engineering, Imperial College London, Exhibition Road, London, SW7 2AZ, a.amis@imperial.ac.uk).

I look forward to receiving comments from the reviewers.

Yours sincerely,

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“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.

Key words: total knee arthroplasty (TKA), instability, soft tissue, primary and secondary restraints, knee biomechanics
1. Introduction

The use of total knee arthroplasty (TKA) to combat the effects of osteoarthritis has become standard practice 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 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 while subjected to axial compressive loading (Haider and Walker 2005; ASTM standard F1223, 2008). 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 2010).

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 Railton, 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 before even 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).

### 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, Gupte et al. (2003) found the ligaments connecting the LM to the posterior aspect of the femur (the meniscofemoral ligaments of Humphry and Wrisberg) 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 that the deep medial collateral ligament (dMCL), whilst not a significant restraint in an intact knee, contributed appreciably in an sMCL-deficient knee over the range 15-90° of flexion, and thus can be described as a secondary restraint. The same study found that the PMC offered 32% of the total restraint to valgus rotation at full extension, however this reduced noticeably in flexion.
The PCL is considered to be only a secondary restraint (Grood et al., 1981), as it can only generate a small moment arm about the centre of valgus rotation compared with the sMCL (Amis et al., 2003).

3.4 Varus Rotation

The lateral collateral ligament (LCL) is the primary restraint to tibial adduction, which causes lateral opening of the knee (Fig. 4) (Gollehon et al., 1987; Grood et al., 1981). It provides 69% of the total restraint to varus rotation at 25° flexion (Grood et al., 1981), although it has been shown that as flexion increases, the LCL becomes more slack and less well-aligned to restrain varus opening (Sugita and Amis, 2001). The PLS and ACL have also been described as secondary restraints, with the PLS only at low flexion angles and the ACL suffering from only generating a small moment arm about the centre of varus rotation (Grood et al., 1981).

3.5 Internal Rotation

With a 5Nm internal torque applied, Robinson et al. (2006) found increased internal rotation of 6-8° between 30-90° flexion after cutting the sMCL, and thus contended that it provided the primary restraint in flexion (Fig. 5). The same study also concluded that the PMC was a primary restraint only when the knee is in an extended position, as it slackens with flexion. Older studies have described the ACL as a secondary restraint to internal rotation, with results showing only a significant increase in internal rotational laxity experienced in cutting posterior structures if the ACL is sectioned first (Gollehon et al., 1987; Lipke et al., 1981).

3.6 External Rotation

The PLS has been acknowledged as the primary restraint to external rotation (Fig. 6) (Grood et al., 1988). The LCL has also been identified as a major stabiliser albeit only when tense at lower flexion angles (Gollehon et al., 1987), whereas the PFL in particular does not slacken with flexion (Sugita and Amis, 2001). Veltri et al. (1996) and more recently Lim et al. (2012)
found the PFL alone can be considered a primary restraint at all angles of flexion, especially compared with the LCL at 60-90° flexion. This was disputed by Pasque et al. (2003) however, who believe that the PFL must be considered as part of the PLS, and does not offer significant restraint alone.

Grood et al. (1988) signified the PCL as a restraint to tibial external rotation at 90° knee flexion, but only having an effect after the PLS has been sectioned. Robinson et al. (2006) found that in response to an applied 5Nm external torque, transecting the sMCL also increased laxity by 3° and 7° at 0° and 90° of flexion respectively, with the dMCL also demonstrating restraint at higher angles of flexion.

4. Evaluating instability of the knee and the contribution of soft tissues

The definition of instability varies between studies, which can be attributed partly to different study backgrounds. For example a clinically-orientated approach may define instability subjectively as the patient’s complaint of the knee ‘giving-way’, or more objectively from measured increases in tibiofemoral joint laxity when a normal knee is modified by injury or arthroplasty (Stoddard et al., 2013). An engineer, however, may repeat the same path of motion after modification and record the decrease in required displacing force as an objective measure of stability (Rudy et al., 1996).

The methods employed to assess soft tissue instability in clinical knee assessment, surgical judgement during an arthroplasty procedure, and in-vitro cadaver testing, are described below.

4.1 Clinical knee assessment

Clinical assessment of knee laxity is essential both prior to surgery, to indicate the type of implant required, and post-surgery (Ishii et al., 2005), to assess whether satisfactory mechanical stability has been achieved. For example, if a patient has a suspected ACL rupture, a clinician may perform either an anterior drawer test, Lachman’s test, or a pivot...
shift test (Bach et al., 1988; Kim and Kim, 1995). The anterior drawer and Lachman's tests impose an anterior translation force on the tibia and the resulting laxity is measured (usually by comparison to the contralateral knee), while the pivot-shift is a more 'dynamic' test which moves the knee in an attempt to elucidate instability.

In an attempt to reduce subjective variation between clinicians performing the assessments, arthrometers were devised for a more quantitative assessment of knee ligament laxity. The KT-1000™, and later the KT-2000™ instrument (MEDmetric®, San Diego, CA, USA), allow the clinician to apply a known force to the patient's tibia, and measure the displacement relative to the fixed femur (Benoit et al., 2006). Initially designed to find ACL or PCL laxity in the intact knee, the KT-2000™ has been subsequently utilised in research comparing the anterior-posterior laxity in PCL-retaining and PCL-substituting TKAs (Ishii et al., 2005).

Other arthrometers include the Telos™ stress device (Metax GmbH, Hungen/ Obbornhafer, Germany), which can be manipulated to test different planes of laxity, including varus/ valgus stress tests (Okazaki et al., 2006; Takeda et al., 2012). However, the Telos device is a means to apply known loads to the knee; the laxity must be measured from pairs of radiographs, taken when the knee was loaded and unloaded.

There are noticeable failings with knee assessment tests. Arthrometers have standardised the direction and magnitude of force applied as well as the measurable displacements, and thus are a less subjective procedure than the original assessment tests. However, like the original tests, there is no obvious way of discovering which ligaments are being scrutinised under the arthrometer loads (Noyes et al., 1980). For example, increased anterior laxity of a knee may not be purely due to an ACL rupture, but could be a result from deficiency of other stabilising structures. There are disagreements between various studies on the repeatability of results of different arthrometers (Cannon, 2002; Forster et al., 1989; Steiner et al., 1990). Furthermore, the forces applied to the knee are much smaller than in normal activity. The circumstances are understandable, as a clinician cannot ethically apply forces that may
cause further damage to the patient’s knee, however it means that a knee with a false negative result for ligament deficiency with an assessment test may still experience instability under normal, higher force activities (Noyes et al., 1980).

There are other clinical methods of measuring movement of knee joints of patients. Gait analysis can utilise motion capture to allow clinicians to view how post-TKA surgery has affected the overall kinematics of the joint. However, problems such as skin movement artefacts mean the motion tracking cannot accurately provide detailed laxity information (Benoit et al., 2006). Instead, video fluoroscopy avoids skin motion effects by capturing series of x-ray images that can be used to reconstruct 3-D kinematics of implants during movements such as rising from a chair, and treadmill running (Fantozzi et al., 2006; Zhao et al., 2007). With the invention of moveable video fluoroscopy systems to increase the viewing field (Zihlmann et al., 2006), more detailed motion trials can be recorded. This could be used in detailing mid-range instability (defined differently by different authors, but generally considered to be at flexion positions up to 90° (Parratte and Pagnano, 2008; Stoddard et al., 2013; Vince et al., 2006; Yercan et al., 2005)) experienced by many TKA patients when stepping downstairs (Stoddard et al., 2013), for example.

4.2 Surgical judgement during arthroplasty

The stability of a TKA is heavily dependent on not only the conforming design of the components, but also on the surgical techniques used to implant the TKA in the patient (Yercan et al., 2005). Therefore, particular protocols are followed during surgery to balance the ligaments (in particular the collaterals) and align the TKA components (Walker et al., 2010).

Generally, if the medial side of the knee is tight, some medial structures such as the MCL, PMC, and pes anserinus will be cut at the tibial insertion to allow correction of the varus deformity (Mihalko et al., 2003; Whiteside, 2002). In laterally tight knees, structures such as the LCL, ITB, PLS and Pop T will be cut at the femoral insertion to allow correction of the
valgus deformity (Kanamiya et al., 2002; Whiteside, 2002). Another release technique named pie crusting can also be utilised on the ligaments, involving multiple stabs of a scalpel on the taut region of the structures, which allows the ligament to be stretched to the desired length without detaching it from the bone (Mihalko and Krackow, 2000).

Many articles have noted issues with attempting to address soft tissue tightness during a TKA procedure. Whiteside (2002) admitted that although medial and lateral releases may help varus/valgus stability, rotational and anteroposterior laxity may be introduced. Ghosh et al. (2012) measured the length-change patterns of the MCL and LCL before and after CR TKA. The study found that, despite a gap balancing technique being used to balance the knee, the collateral ligaments slackened more than in the natural knee after CR TKA when the knee was flexed.

It can be suggested that the testing of soft tissue balance is too dependent on the experience of the surgeon. Mihalko et al. (2003) describe two different techniques to test ligament balancing: distraction testing and trial components. Distraction of the joint with laminar spreaders or tensors allows the surgeon to assess the flexion and extension gaps with spacer blocks in place. Alternatively, trial components may be fitted into the joint space, and varus/valgus stress tests can assess medial and lateral soft tissue balance.

The use of spacer blocks to determine equal joint spacing in flexion and extension by sight is very subjective. Performing a varus/valgus stress test at 0° and 90° flexion may give a ‘feeling’ of laxity at these angles, but does not address the balance at angles between these limits (D’Lima et al., 2011). This is problematic, as an implanted TKA may experience “mid-range instability” if the soft tissue is not tense within 0-90° flexion (Stoddard et al., 2013; Yercan et al., 2005).

Vince et al. (2006) argued that trying to prevent mid-range instability by balancing a knee at mid-flexion would cause the knee to be too tight to allow for full extension. Perhaps, therefore, revising to a more conforming TKA implant offering more varus/valgus restraint
would be suitable in cases where the patient suffers from mid-range instability. However, since a surgeon largely bases varus/valgus stability on ‘feel’, the authors suggest that a more quantitative approach to determining laxity would be useful in helping less-experienced surgeons decide the correct implant.

4.3 *In vitro cadaver testing*

*In-vivo* testing on subjects has advantages such as being able to perform normal activity, but it is heavily constrained by ethical and practical issues (Kessler et al., 2009). For example, it would be highly unfeasible to subject a single patient to multiple surgeries for different implant designs comparisons, or to perform activities that could risk soft tissue damage. Working in-vitro on cadavers resolves such problems. It is possible to compare different implant designs, positioning or surgical techniques on the same specimen, minimising inter-subject variation. Although accurate anatomic replication of active restraints such as muscle forces requires further investigation, there is more control on passive soft tissue restraint than with in-vivo testing.

Noyes, Grood and Butler helped pioneer laxity testing to determine the passive restraints from the primary knee ligaments (Butler et al., 1980; Grood et al., 1981; Noyes et al., 1980). By imposing known displacements/rotations to the tibia at fixed flexion angles and measuring the reduction of displacing force required by cutting ligaments around the knee, the percentage contribution of various ligaments to resisting that movement can be calculated (Race and Amis, 1996).

The limits of laxity across the arc of knee flexion-extension can be described as the envelope of passive knee motion (Blankevoort et al., 1988). During the natural arc of flexion/extension, the tibia is free to rotate or displace in the other five DoF, leading to the passive path of motion. Thus, by applying forces and moments to the tibia along this arc to a limit, beyond which damage to the specimen may occur (Blankevoort et al., 1988), an envelope of laxity along the arc can be determined (Bull et al., 2008).
The introduction of robotic technology to simulate and record more complex loading conditions on knee joints (Fujie et al., 1993) has allowed studies into the “in-situ” force (Fujie et al., 1995) experienced by ligaments during predefined movements.

5. Ligamentous laxity and/or deficiency and its influence on implant constraint

As a general guide, surgeons are recommended to choose implants with as minimal amount of constraint as possible to achieve stability (Naudie and Rorabeck, 2004). Any increase in the constraint in the prosthesis also increases its capability to transmit loads to the fixation; it is preferable for the loads to be transmitted by the soft-tissue stabilisers (Fig. 7). A corollary is that, because constraint allows greater loads to be transmitted, the fixation has to become more massive to prevent loosening, and that is inevitably more destructive during insertion and leaves fewer options if revision is needed.

On that basis, the most common implants used are CR and PS TKAs, with gap balancing and releases if required to restore soft tissue symmetry. However, if there is still persistent laxity, more constraint will be required (McAuley and Engh, 2003). In the case of revisions when a primary TKA needs to be recovered after failure, the soft tissue envelope around the knee may be disrupted or the associated bone loss may mean the attachment sites of the MCL and LCL are lost (Sculco, 2006).

More-constrained designs, whilst offering more global stability than CR and PS TKAs, rely less on soft tissue contributions and thus increase the stresses on the implant-bone interface and increase risk of early loosening (Nelson et al., 2003; Fig. 7). If these more-constrained devices fail, their revision is a serious task; therefore it is important that surgeons receive guidance about the limits of use of less-constrained devices so that they do not need to resort unnecessarily to the more-invasive procedures when in doubt about the ability of the lesser device to maintain knee stability in the face of specific soft tissue deficiencies. However it is difficult to judge how much soft tissue deficiency/laxity necessitates this extra constraint (Morgan et al., 2005), and there is little published data which might guide this.
Girard et al. (2009) performed a retrospective analysis on TKAs in valgus knees, and identified, following the use of tensioning devices and spacer blocks, a threshold of 5° residual valgus laxity in extension and 3mm in tibiofemoral gap difference between flexion and extension, which if exceeded were indications for the use of more-constrained condylar implants rather than a normal PS TKA.

Sculco (2006) noted that the process of determining level of constraint is subjective, but recommends that, if after spacer blocks or laminar spreaders have attempted to introduce soft tissue symmetry, laxities of 7-10mm under stress tests suggest a more-constrained implant is required. Sculco (2006) further advises on the choices between the constrained designs, believing that constrained condylar implants are suitable if the MCL and/or LCL are present, but remain lax even after attempted balancing. However, if one of those ligaments is either deficient or missing, a rotating hinged implant would be required to restore stability.

Gustke (2005) reported a more specific plan for implant choice based upon preoperative ligament function, confirmed through physical varus/valgus stress examinations and radiographs. An LCL lax knee may suffice with a constrained condylar design, as well as an MCL lax knee if the ligament can be reconstructed. However if the MCL is absent, or both MCL and LCL are insufficient, then only a rotating hinge implant gives acceptable stability. What is universally agreed, is that a rotating hinge design should only be considered as a last resort if all other less constrained implants cannot provide sufficient stability.

6. Conclusion

This review discussed the different methods of evaluating instability in an intact and implanted knee, as well as present current ideas of primary and secondary passive restraint to anterior/ posterior drawer, internal/ external rotation and varus/ valgus rotation. Clinical tests can be performed quickly on patients to determine the laxity of the knee approximately, but cannot accurately define the health of a specific ligament. In vitro testing can investigate specific ligaments in turn for a more detailed description of the passive restraint of the knee,
although instability due to active restraints such as muscle forces is difficult to replicate. More research is required on how the ligaments are affected by implantation of a TKA, to decide which implant is suitable for the patient.

It is imperative to have greater understanding of whether the standard soft tissue releases during arthroplasty actually improve the kinematics of the TKA to an idealised normal intact state, or whether some actually further introduce instability during various angles of knee flexion/extension. For example, with a medially tight knee, releasing medial structures such as the sMCL may correct the varus deformity (Whiteside, 2002) and, after choosing the correct TKA component thickness to tense the collateral ligaments, improve the varus-valgus restraint that the LCL and MCL can now give, becoming more tensed while the limb is in the corrected alignment. However if the sMCL is considered a secondary restraint to anterior drawer (Butler et al., 1980) and a primary restraint to internal rotation (Robinson et al., 2006), is the stability in these planes of motion then adversely affected by the release?

The authors of this study suggest that more research is required on the biomechanical variations caused by soft tissue deficiency as well as on the controlled releases performed by surgeons, so that a more quantifiable assessment can be made by less experienced surgeons on the choice of TKA implant for the specific patient.

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Total knee arthroplasty in valgus knees: Predictive preoperative parameters influencing a


Fig. 1. Ligamentous restraints to anterior displacement, in A) lateral, B) anterior, and C) medial views. Soft tissues highlighted in red signify primary restraint, and in yellow signify secondary restraints. ACL = anterior cruciate ligament, dMCL = deep medial collateral ligament, sMCL = superficial medial collateral ligament, MM = medial meniscus.
Fig. 2. Ligamentous restraints to posterior displacement, in A) lateral, B) anterior, and C) medial views. Soft tissues highlighted in red signify primary restraint, and in yellow signify secondary restraints. Pop T = popliteus tendon, PFL = popliteofibular ligament, PCL = posterior cruciate ligament, PMC = posteromedial capsule.

Fig. 3. Ligamentous restraints to valgus rotation, in A) lateral, B) anterior, and C) medial views. Soft tissues highlighted in red signify primary restraint, and in yellow signify secondary restraints. PCL = posterior cruciate ligament, dMCL = deep medial collateral ligament, sMCL = superficial medial collateral ligament, PMC = posteromedial capsule.

Fig. 4. Ligamentous restraints to varus rotation, in A) lateral, B) anterior, and C) medial views. Soft tissues highlighted in red signify primary restraint, and in yellow signify secondary restraints. Pop T = popliteus tendon, PFL = popliteofibular ligament, LCL = lateral collateral ligament, ACL = anterior cruciate ligament.

Fig. 5. Ligamentous restraints to internal rotation, in A) lateral, B) anterior, and C) medial views. Soft tissue highlighted in red signify primary restraint, and in yellow signify secondary restraints. ACL = anterior cruciate ligament, sMCL = superficial medial collateral ligament, PMC = posteromedial capsule.

Fig. 6. Ligamentous restraints to external rotation, in A) lateral, B) anterior, and C) medial views. Soft tissues highlighted in red signify primary restraint, and in yellow signify secondary restraints. Pop T = popliteus tendon, PFL = popliteofibular ligament, LCL = lateral collateral ligament, PCL = posterior cruciate ligament.

Fig. 7. Diagrams of a right knee demonstrating increasing surgical invasiveness and bone loss, going from A) intact, B) cruciate-retaining implant, C) posterior-stabilised implant, to D) constrained condylar implant. With increasing prosthetic constraint, the load transmission moves from the soft tissues to the implant fixation; this is illustrated for a knee abduction (valgus) moment. In A) the arrows signify the compressive lateral tibiofemoral contact point and tensile medical collateral ligament (MCL) force restraining the applied valgus moment,
which is similarly replicated in B) and C). However in the case of D) with a deficient or absent MCL, the moment is resisted by implant-bone interface stresses distributed along the wall of the box mechanism and the tibial/femoral intramedullary stems.
Table 1 A summary of studies investigating ligamentous and soft tissue restraints in intact knees.

<table>
<thead>
<tr>
<th>Lead Author</th>
<th>Sample Type</th>
<th>Method</th>
<th>Ligament/ Soft tissue investigated?</th>
<th>Number of samples</th>
<th>Kinematic test (referenced to the tibia)</th>
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<tbody>
<tr>
<td>Butler et al. (1980)</td>
<td>In vitro</td>
<td>MTS 1 DoF</td>
<td>APCLPML</td>
<td>11</td>
<td>Ant/Post ± 5mm</td>
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<td>Grood et al. (1981)</td>
<td>In vitro</td>
<td>MTS 1 DoF</td>
<td>APCLPML</td>
<td>10</td>
<td>Var/Val (± 6mm medial/lateral joint opening)</td>
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<tr>
<td>Fukubayashi et al. (1982)</td>
<td>In vitro</td>
<td>MTS 4 DoF</td>
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<td>9</td>
<td>Ant/Post 125N</td>
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<tr>
<td>Sullivan et al. (1984)</td>
<td>In vitro</td>
<td>MTS 5 DoF</td>
<td>APCLPML</td>
<td>10</td>
<td>Ant/Post 100N</td>
</tr>
<tr>
<td>Daniel et al. (1985)</td>
<td>In vivo/in vitro</td>
<td>Arthrometer</td>
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<td>460^a</td>
<td>Ant/Post 89N</td>
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<td>Gollehon et al. (1987)</td>
<td>In vitro</td>
<td>MTS 5 DoF</td>
<td>•PCLPML</td>
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<td>Ant/Post 100N, Var/Val 10Nm, Int/Ext 4.5Nm</td>
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<td>Grood et al. (1988)</td>
<td>In vitro</td>
<td>Rig with tibia free hanging/vertical</td>
<td>APCLPML</td>
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<td>Ant/Post 100N, Var/Val 20Nm, Int/Ext 5Nm</td>
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<td>Levy et al. (1989)</td>
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<td>Ant/Post 100N, Var/Val 20Nm, Int/Ext 6Nm</td>
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<td>Shapiro et al. (1991)</td>
<td>In vitro</td>
<td>Cruciate-attached force transducer</td>
<td>•APCLPML</td>
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<td>Ant 78N, Var/Val 15Nm, Int/Ext 10Nm</td>
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<td>Race and Amis (1996)</td>
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<td>MTS 4 DoF</td>
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<td>Ant/Post ± 6mm</td>
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<td>Finite element model</td>
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<td>MM, LM</td>
<td>-</td>
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<td>Jilani et al. (1997)</td>
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<td>Finite element model</td>
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<td>MM, LM</td>
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<td>Hoher et al. (1998)</td>
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<td>Robotic</td>
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<td>8</td>
<td>Post 110N with popliteus muscle 44N</td>
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<tr>
<td>Krackow and Mihalko (1999)</td>
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<td>Rig with tibia free hanging/vertical</td>
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<td>ITB, MM, LM</td>
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<td>Authors</td>
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<td>Methodology</td>
<td>Parameters</td>
<td>Force (N)</td>
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<td>Kanamori et al. (2000)</td>
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<td>Ant 134N</td>
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<td>Gupte et al. (2003)</td>
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<td>Pasque et al. (2003)</td>
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<td>Rig with tibia</td>
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<td>Post 100N, Var 10Nm, Ext 5Nm</td>
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<td>Gabriel et al. (2004)</td>
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<td>Robotic</td>
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<td>Ant 134N, Rotatory (Val 10Nm, Int 5Nm)</td>
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<td>Li et al. (2004)</td>
<td>In vitro</td>
<td>Robotic</td>
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<td>Post 130N with quads 400N and hams 200N</td>
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<td>Shirazi-Adl and Moglo (2005)</td>
<td>In silico</td>
<td>Finite element model</td>
<td>MM, LM</td>
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<td>Ant/Post 100N</td>
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<td>Robinson et al. (2006)</td>
<td>In vitro</td>
<td>MTS 4 DoF</td>
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<td>14</td>
<td>Ant/Post 150N, Val 5Nm, Int/Ext 5Nm</td>
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<td>Zantop et al. (2007)</td>
<td>In vitro</td>
<td>Robotic</td>
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<td>Ant 134N, Pivot shift (Ant 134N, Val 4Nm, Int 4Nm)</td>
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<td>Petersen et al. (2008)</td>
<td>In vitro</td>
<td>Robotic</td>
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<td>Post 134N, Val 10Nm, Int 5Nm</td>
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<tr>
<td>Battaglia et al. (2009)</td>
<td>In vitro</td>
<td>Robotic</td>
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Of the 460 samples, 33 were cadaver knees, 338 were normal patients, and 89 were patients with unilateral ACL rupture.
Table 2 A summary of studies investigating ligamentous and soft tissue restraints in total knee arthroplasty implanted-knees.

<table>
<thead>
<tr>
<th>Lead Author</th>
<th>Sample Type</th>
<th>Method</th>
<th>Ligament/ Soft tissue investigated?</th>
<th>Arthroplasty</th>
<th>Number of samples</th>
<th>Kinematic test (referenced to the tibia)</th>
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<tr>
<td>Nagamine et al. (1995)</td>
<td>In vitro</td>
<td>E. E. test rig (^a)</td>
<td>•</td>
<td>TKA</td>
<td>8</td>
<td>Var/ Val 45N applied at ankle, Int/Ext 3Nm Passive flexion, Var/ Val 150N</td>
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<tr>
<td>Takahashi et al. (1997)</td>
<td>In vivo</td>
<td>Pressure film (intraop)/ Arthrometer (postop)</td>
<td>• •</td>
<td>CR TKA</td>
<td>63</td>
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<tr>
<td>Matsueda et al. (1999)</td>
<td>In vitro</td>
<td>Cable/spring set-up</td>
<td>• • • • • Semi M, ITB</td>
<td>CR TKA</td>
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<td>Var/ Val 10Nm</td>
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<td>Li et al. (2001)</td>
<td>In vitro</td>
<td>Robotic</td>
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<td>CR and PS TKA</td>
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<td>Passive flexion with quads 400N and hams 200N</td>
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<td>Saecki et al. (2001)</td>
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<td>E. E. test rig (^a)</td>
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<td>Ant/ Post 35N, Var/ Val 10Nm, Int/Ext 1.5Nm Var/ Val 10Nm, Int/ Ext 10Nm</td>
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<td>ITB</td>
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<td>Var/ Val 10Nm, Int/ Ext 10Nm</td>
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<td>Most et al. (2003b)</td>
<td>In vitro</td>
<td>Robotic</td>
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<td>CR and PS TKA</td>
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<td>Passive flexion without muscle loads</td>
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<td>Barink et al. (2005)</td>
<td>In silico</td>
<td>Finite element model</td>
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<td>CR TKA</td>
<td>-</td>
<td>Ant/ Post 100N, Var/ Val 10Nm, Int/ Ext 3Nm</td>
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<td>Ishii et al. (2005)</td>
<td>In vivo</td>
<td>Arthrometer</td>
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<td>CR and PS TKA</td>
<td>77</td>
<td>Ant 133N, Post 89N</td>
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<tr>
<td>Most et al. (2005)</td>
<td>In vitro</td>
<td>Robotic</td>
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<td>CR and high-flexion CR TKA</td>
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<td>Passive flexion with quads 400N and hams 200N</td>
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<td>Heesterbeek et al. (2010)</td>
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<td>Calibrated spring (intraop)/</td>
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<td>ITB</td>
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<td>Var/ Val 15Nm</td>
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<td>Kesman et al.</td>
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<td>PS TKA</td>
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<td>Var/ Val stress test</td>
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<td>In vivo</td>
<td>Arthrometer</td>
<td>-</td>
<td>CR and PS TKA, mobile-bearing</td>
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<td>Var/Val 150N</td>
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<td>Koh and In</td>
<td>In vivo</td>
<td>Arthrometer</td>
<td>• • Semi M</td>
<td>PS TKA</td>
<td>104</td>
<td>Var/ Val stress test</td>
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</table>

Key to content: ACL = anterior cruciate ligament, PCL = posterior cruciate ligament, LCL = lateral collateral ligament, PLS = posterolateral structures, MCL = medial collateral ligament, PMC = posteromedial capsule, Semi M = semimembranosus tendon, ITB = iliotibial band, CR TKA = cruciate-retaining total knee arthroplasty, PS TKA = posterior-stabilised total knee arthroplasty, Ant = anterior translation, Post = posterior translation, Int = Internal rotation, Ext = external rotation, Val = valgus rotation, Var = varus rotation, Quads = quadriceps muscles, Hams = hamstring muscles.

*Knee kinematic testing rig (Experimental Engineering, Little Rock, AR, USA)*